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INDUSTRIAL RADIOLOGY
and
RELATED PHENOMENA

INDUSTRIAL RADIOLOGY

and

RELATED PHENOMENA

*(X-Rays, Gamma Rays, Physical Metallurgy,
and Magnetic Analysis)*

Page 338, Fig. 3—Solidus and Liquidus.

Page 522, top left of page 522—Hydrochloric acid

By

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FIRST EDITION

Published by

AIRCRAFT X-RAY LABORATORIES
HUNTINGTON PARK, CALIFORNIA

1943

724-1
1943
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To

My Mother

*whose unrelinquished faith, courage, and sacrifice
have formed the principal basis of
my academic endeavor.*

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FOREWORD

In the preparation of this book, it has been the intention of the author to explain industrial radiography in such a manner that it can be readily understood by various laymen in the industrial field.

Three years ago very little information was to be found relative to the use of x-rays on industrial materials. A thorough search was made in various institutions and libraries for material that would be helpful to inspectors, purchasing agents, foundry personnel, and engineers, in determining the proper use of x-rays for industrial inspection. Such material that was available was practically all relative to the medical profession.

Through the use of the facilities of the Aircraft X-Ray Laboratories and through the competent work of the author, H. M. Muncheryan, our chief physicist and director of research, the development of this book mostly from our experimental findings in this vast and incompletely developed field has been made possible. Many hours of research and development have been necessary in the preparation of all the material given in this book. Much of this information has been instigated by the rapid increase of aircraft production in the western states and also by the rigid requirements of the various procuring agencies; and, consequently, x-ray inspection has expanded considerably. It was further necessary that personnel had to be trained to understand the methods and proper procedure of x-ray inspection. The scheme further consisted of knowing the type of material under examination and what information could be obtained by such an inspection. It is the author's desire, in writing this book, to render the average layman as well as the technical man a comprehensive and practical knowledge pertaining to the application of x-rays and related fields in various phases of industry.

One of the most important factors in x-ray inspection resides in the adaptability of x-rays to the examination of various types of materials, assemblies, and the structures of various assemblies, castings, forgings, etc. It is the anticipation of the author and ourselves that this book will serve a great number of people in

making various decisions on types of material to be used industrially not only in war production but in many essential activities.

As a result of the large production program, many changes have been made in industrial x-ray equipment which has enabled the x-ray laboratories to produce x-ray inspection at low cost and on a production basis. Many improvements have also been made in the type of x-ray films that are now available, and we can fully expect to find many more improvements in the future in both x-ray machines and films.

I wish to express my sincere appreciation for the untiring effort of Prof. Muncheryan in the preparation of this book. Much of this work was carried on after his regular duties as chief physicist of the Aircraft X-Ray Laboratories.

GEORGE E. NEWTON, *President,*
Aircraft X-Ray Laboratories.

Huntington Park, California
May 14, 1943

PREFACE

Within the past few years, the Nation's engagement in unprecedented production quotas has wrought tremendous changes in industry as well as in business, that the production of sound materials in line with an effort to hasten the manufactured product to the assembly lines has become affiliated with reliable inspection and testing preliminaries commensurate with speedy production. In this connection, x-rays have played a tremendous part in the furtherance of improved manufacturing processes and materials of sound and dependable quality from a technical viewpoint. Thus, recognition rendered the industrial radiology, then, should be one of obligation of the first magnitude. Yet, the information dealing with the practical applications of x-rays, and gamma-rays to the non-destructive examination of industrial materials has been rather meagre. Instigated by such a need, and further importuned by his friends and colleagues, the author has undertaken the preparation of this edition.

This book, *Industrial Radiology and Related Phenomena*, has developed partly from a course of lectures under the title "Non-Destructive Inspection of Materials" given by the author at the University of Southern California, and partly by the author's experience and efforts expended at the Aircraft X-Ray Laboratories, with which he is consolidated at present. The work has been further supplemented by the technical contributions, to the field, of many professional workers, x-ray research laboratories, technical societies, industrial metal manufacturing and founding firms, and by the manufacturers of x-ray and metallographic equipment. It is, therefore, suited for those who desire to obtain a broad idea of the principles and practice of the most modern methods of radiation and metallographic engineering and of diagnosis of industrial materials.

In preparing this book, an effort has been made to present the material with such pedagogical attitude as will give the reader a comprehensive perspective of the fundamental principles of atomic theory and electricity preparatory to the discussions on x-ray generation, apparatus, circuits, and applications, and perti-

nent metallurgical aspects having regard to the fabrication, processing, and subsequent inspection of materials of industry. The selections of topics as well as the method of presentation has been mainly based upon the experience gained through the author's giving a series of lectures on the above-mentioned subjects to various groups of classroom audience and other auditors. Indeed, it is believed that some portions of the material have been put in print for the first time.

Particular endeavor is made to use simple language consistent with scientific writing so that any person with an elementary knowledge of pre-academic sciences can understand it when the text is studied progressively. Further attempt is made in carefully arranging the plan that one subject gradually leads to the other by logical steps, thus preparing the reader to more intelligently understand the increasingly more specialized discussions. It is therefore hoped that this work will meet the needs of students, engineers, inspectors, foundrymen, and those interested in the study of industrial radiology and pertinent phases of physical metallurgy, being adapted particularly to classroom teaching.

The author further believes that in writing a book of this character, no account of the underlying principles of radiology can dispense with at least a limited amount of mathematical discussions and derivations, many of which are illustrated by examples based on common experience. Furthermore, in order that the reader may secure a firmer grasp of these applications, an extensive discussion on atomic structure, and nuclear and extranuclear phenomena relevant to the constitutional structures of metals and alloys of industry, have been included in this treatise with the view of correlating the theoretical and practical aspects of radiological diagnoses of materials. In this connection, the author has selected and prepared specific illustrations of radiographs and photomicrographs of both sound and defective materials, presenting them from a comparative viewpoint. Indeed, he realizes that that part of the book treating the examination of metals by magnetic flux is rather limited, firstly, because the scope of the text does not permit to present a detailed discussion of the subject in the space of this volume, and secondly, in view of other published information of high order having been available on the subject.

It is sincerely anticipated that the present treatise will bridge the gap between the empirical and scientific methods underlying the subject of industrial radiology both with x-rays and gamma rays. It is further hoped that the book will prove useful as an academic course, as a reference to the practitioner, and to those many who are concerned with x-ray profession and inspection and who may have acquired their knowledge through rather empirical practice and thus may lack the fundamental physical and technical foundations in the field to which they intend to adapt themselves. Hence, the author and the publishers of this book jointly take pleasure in sharing with the reader the benefit of the experience gained in the field in the furtherance of improved methods and more recent developments of radiological and pertinent inspections particularly of commodities having regard to public safety and comfort, and look forward to the creation of a closer relationship between material production and sound methods of inspection.

The author wishes to take this occasion to express his indebtedness to those many institutions, manufacturing firms, and individuals who have furnished some of the illustrations, technical data on their more recent research, and valuable suggestions in making this volume possible. The author gratefully presents them as follows:

General Electric X-Ray Corporation
Bausch & Lomb Optical Company
Aircraft X-Ray Laboratories
Eastman Kodak Company
Aluminum Company of America
The Dow Chemical Company
Machlett Laboratories, Inc.
Westinghouse X-Ray Corporation
The Kelley-Koett Manufacturing Co., Inc.
The International Nickel Company
Philips Metalix X-Ray Corporation
Climax Molybdenum Company
The National Photocolor Corporation
Agfa Ansco Corporation
The American Magnesium Corporation
National Bureau of Standards
American Society for Metals

American Society for Testing Materials
Eureka X-Ray Tube Corporation
Wilson Mechanical Instrument Company, Inc.
American Machine and Metals, Inc.
Magnaflux Corporation
Shore Instrument Manufacturing Company
Combustion Engineering Company
Braun Corporation
Ampco Metal, Inc.

Finally, the author takes pleasure in acknowledging his obligations to Mr. George E. Newton, a most respected pioneer and an advocate of radiation inspection, who has made the entire facilities of the Aircraft X-Ray Laboratories available to the author to make various investigations and obtain necessary data preparatory to the challenge of this work.

H. M. MUNCHERYAN.

Huntington Park, Calif.
May, 1943

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INDUSTRIAL RADIOLOGY AND RELATED PHENOMENA

CHAPTER I

INTRODUCTION

1. Matter and Energy.—For centuries it was known that matter consisted of discrete particles which could be converted from one form into another without the destruction of the particles entering into the particular transformation. In like manner, energy, which may evolve as a by-product of a chemical reaction, and from various mechanical motions, or from sources of electrical origin, could be transformed from one state into another depending on the medium bringing forth these manifestations. Therefore, these two great entities, which may be regarded as making up the universe, could neither be created nor destroyed, and that each of which was “conserved.” Hence, the nineteenth century classical theory became established on two primordial laws—*the conservation of matter, and the conservation of energy.*

Following the establishment of the theory of conservation of matter, and of energy, toward the latter half of the 19th century, the physicist became inclined to approach this subject not only scientifically but philosophically as well. About the year 1920, with the generalization of Planck’s quantum theory together with Einstein’s photoelectric concept, it became obvious that light, a form of radiant energy, possessed dual characteristics—undulatory, and corpuscular. In the first case, light was represented as a wave motion in the ether, while in the second case, it was regarded as a shower of corpuscles of energy, which, in terms of modern version, are the “*quanta*.” The year 1930 witnessed the complete removal of all doubts regarding De Broglie’s bold statement, in 1924, that particles of matter possibly are associated with certain undulatory characteristics.

Recent experiments in artificial transmutation of matter have conclusively proved the interconversion of matter and energy, as

evidenced, in the collision processes, by the appearance of a high frequency photon as an electron or a positron during a photonic encounter with the nucleus of the atom irradiated. Other experiments with high speed protons, and neutrons, have further indicated the conversion of energy into mass. On the other hand, during the disintegration of a radioactive substance, in consequence of some kind of nuclear catastrophe, and subsequent projection of alpha-particles and beta-rays from this structure, a vast quantity of energy is released, a definite evidence that matter is transformed into energy.

The energy liberated as a result of the conversion of matter is enormously high, and the mass equivalent of this energy may be given by the expression

$$\Delta m = \frac{\Delta E}{c^2} \quad (1)$$

where, ΔE is the energy of the photon, and c is the velocity of light. In the case of the sun, which loses by radiation approximately four million tons of its mass per second, the energy thus liberated is inconceivably large. Yet, it will take trillions of years to annihilate the mass of the sun in this manner, which rate is only a small amount compared to that of certain stars.

In a later section, the subject of interconversion of mass and energy relations in the formation of atomic nuclei will be treated more particularly and search for ultimate facts will be brought to light as fully as the scope of this book will permit.

2. The Atom, Ions, and Electrical Charges.—As evidenced from the foregoing, *matter* is a divisible entity the ultimate of which is not necessarily conserved in the structure of the *atom*. The atom, however, is the smallest structural unit of matter that possesses all the characteristics of the original matter. Since, numerically the mass of an atom in terms of Oxygen of atomic weight 16 is approximately an integral value, it is suggestive of Prout's hypothesis that the building unit of an atom is the element Hydrogen, which has an approximate atomic mass of 1. However, we shall modify this in terms of modern interpretation by stating that the nuclei of atoms are made up of neutrons and protons.

Prout's hypothesis is superseded by Rutherford's nuclear atom theory, which presupposes that the essential mass of the atom is concentrated in the nucleus composed of *alpha-particles*, *neutrons*, and *protons*, and surrounded by negatively charged planetary particles, called *electrons*, in constant motion around the nucleus. The protons which are in excess of the neutral portion of the nucleus charge it positively. Since an atom at rest is electrically neutral, it follows that the number of positive charges, or protons, must be associated with an equal number of electrons in the extranuclear region of the atom. The radius of an atom being of the order of 10^{-8} cm, the motion of the planetary electrons in a normal atom is limited to this confine.

The mass of an atom is determined by the number of elementary unit particles making up the nucleus and is identified with its *atomic weight*, while the number of excess nuclear positive charges corresponds to the *atomic number* of that atom.

In explaining the stability of a normal atom, reference should be had to the quantum theory, which assumes, in view of Bohr theory, that the motion of the extranuclear electrons is governed by the ordinary laws of mechanics, and electrostatics. Accordingly, to satisfy these conditions, the force of mutual attraction between the positive and negative charges in a normal atom is equivalent to the centrifugal force tending to disrupt the planetary electrons from their normal orbits of motion, as given by the following equation:

$$\frac{m\tau^2}{r} = \frac{Ec}{r^2} \quad (2)$$

where, m is the mass of the electron and τ its velocity, E and c are respectively the nuclear positive charge and the negative electronic charge, and r is the distance between the two charges. Furthermore, an electron in its motion in an orbit accelerates, but does not radiate—a fact which the classical theory totally fails to explain.

Whenever an atom absorbs energy in excess of that retaining the electron in motion in its normal orbit, the atom becomes *excited*, and the electron moves to an orbit of higher stationary state. In an extreme case of *excitation*, however, the electron is

completely dissociated from the atom, when, the atom becomes a positively charged *ion*.

The fact that the electron bears a negative charge, and when it is isolated from the original atom the latter becomes a positive ion, it may be inferred that an atom is a source of electricity of unit magnitude. In order that an atom may produce these charges, it must first dissociate into positive ions and a corresponding number of negative charges constituted by the *planetary*, or *valency*, *electrons* of the atom.

It will be assumed, at this time, that the foregoing will give, as much as space permits, a virtual picture of the nature of electricity as seen in the light of the Rutherford-Bohr model of the dynamic atom.

3. Electric Currents and Potentials.—Reference was made above that the dissociation of an atom into a negative and a positive ion constituted the origin of electricity. In metallic conductors, however, the electrons are projected at comparatively great distances from the nuclei of the atoms. These electrons are called "*free electrons*." They are easily removed from the parent atom, or atoms, under the attraction or repulsion of an electrical force external to the atom. Under these conditions the electrons will acquire an average velocity of drift in the direction of the electric *force gradient*, producing a current of electricity. The force which causes the migration of electric charges in a conductor is known as the *electromotive force*, or, *electric potential*.

Atoms may dissociate by various ways, as in a chemical reaction, or in an electronic encounter during a collision process in a discharge tube, and under the influence of magnetic fields, as in electric dynamos. The isolation of the electrons from the atoms at one end of the conductor and their aggregation at the other end produces a difference of potential between these two points, which, when brought together to make a contact, cause a momentary flow of current through the conductor. When the electrical stress between the negative and the positive ends of the conductor is thus removed, the atoms within the conductor tend to resume their original state by the recombination of the negative and positive charges.

In view of the "*free electron*" structure of the atoms, substances may be classified as *conductors*, and *non-conductors* or

insulators, according to the number of free electrons they possess. All substances contain free electrons to some extent; and, those that contain a large number of these electrons are called conductors, while those that are devoid of free electrons, or contain merely a few electrons per given volume, are known as insulators, or *dielectric substances*.

In a discharge tube, filled with a readily ionizable gas, the application of a difference of potential between the two ends of the tube will produce *ionization* of the gas, which, in turn, will cause a flow of current across the discharge medium. If now the gas of the tube is rarefied by pumping it out, and the pressure within is lowered to a few millimeters of mercury, the impressed potential on the electrodes will produce a stream of *cathode rays* from the negative electrode or the cathode. These rays, as will be seen presently, play an important part in the production of *x-rays*.

The migration of charges in an electrolytic process is the reverse of that in a discharge tube. In a solution of an electrolyte, the migration of the unlike polar ions to the respective electrodes will generate a potential difference between the terminals of the electrodes. Hence, when an electrical contact is established between the external ends of the electrodes, a current will flow from the negative to the positive terminal. As is evident, the electrolytic solution generates its own current. A slightly modified process, which is known as *electrolysis*, is used in the deposition of the positive ions on the negative pole of the electrolytic circuit (commercially known as electroplating).

4. Some Considerations of X-rays.—The importance of x-rays stands as one of the foremost of all the discoveries made in pure science. Soon after Roentgen announced his discovery to the world, the use of x-rays spread rapidly in the field of medicine. Throughout the entire scientific world his experiments were repeated and extended, and many laboratories were established in an endeavor to further the research in this field because of its important practical applications in applied science as well as in medicine.

In recent years the use of x-rays is so extended that it provides us with a "diagnosis" not only in medicine but in industrial problems as well. It provides us with an inside view of matter,

whereby we can have a physical concept, not only of the homogeneity (or inhomogeneity!) of matter, but also of the arrangements of the electrons and the nuclear bodies in the atom.

X-rays are produced when a stream of high velocity cathode rays impinge upon the target of an x-ray tube. The rays penetrate the target to a depth of a few microns, transferring their kinetic energy to the firmly bound electrons in the innermost levels of the target atoms. As a result, the electrons in these levels are accelerated radially to the nucleus, producing radiations with extremely high frequencies. These radiations from the target constitute the *x-rays*.

The penetrating quality of x-rays is dependent upon the applied potential on the cathode and upon the nature of the target metal. Metallic elements having high atomic weights produce x-rays of high penetrating quality, since the radiation wavelengths from these atoms are much shorter than that of metals of low atomic weights.

As visible light, x-rays are electrically neutral, and propagate from the anti-cathode, or, the target, in straight lines. They are partially absorbed by matter when they impinge on it. X-rays may be diffracted, refracted, and reflected from crystal lattice surfaces. Atoms having relatively low atomic weights scatter the x-rays, producing secondary radiations, and those having high atomic weights tend to absorb the x-rays. The emission of x-rays is closely associated with processes involving *photoelectric emission*—in fact, one is the reverse process of the other.

When x-rays traverse matter, they are differentially absorbed by it, the magnitude of absorption being dependent on the density and the thickness of the material traversed. This property of x-rays is utilized in industry to detect the internal defects of metals and thereby to increase the safety factors of structural materials having regard to the security of human life.

The inspection of materials by x-rays is further supplemented by magnetic analysis of sub-surface defects in steels, and by gamma-rays where there is a large scale inspection of heavy materials and where the cost of large capacity x-ray equipment is of primary concern. These tests are often accompanied by physical tests and qualitative micrographic analysis. It is, therefore, deemed necessary to include the subject of metallurgy and related

metallurgical considerations in this text in order to convey to the reader a better understanding of the relation of the constitutions of various materials of industry to the methods of production.

Since the purpose of this book primarily resides in the phenomena involving the generation, character, and application of x-rays to industrial examination of materials, a complete treatment of this subject will be found throughout the accompanying discussions.

5. Electromagnetic Waves.—The discovery of electromagnetic waves dates back to 1887-1888, when, Hertz observed that an oscillatory electric discharge set up a train of electromagnetic vibrations in space, and that the character of these wave trains was in common in many ways to light waves. The theory is an exact prediction by Maxwell in 1865, but it was never demonstrated in experimental reality at his time. The theory introduces the electromagnetic wave trains as radiations of accelerated charges. According to this precept, an accelerated charge must always radiate, which, as we shall see later, must be accepted with reservation in view of Bohr's extension of the radiation hypothesis.

Radiations of all forms propagate in space in the form of wave trains. These are transverse vibrations set up by the "*inter-linkage*" of the vector effects of disturbances of electrical origin executing simple harmonic motions. But, establishing a disturbance of this character will involve energy, the rate of travel of which is proportional to the product of the electric and magnetic vectors, as set forth in Poynting's theorem. What attribute the radiation energy possesses while speeding through space can not be determined in a fundamental fashion except that of the manifestations effected on material objects experiencing the effects of this energy.

According to electromagnetic wave theory, we assume that the energy from any radiating source is given in *ergs* per cubic centimeter of the space traveled. Again, we would not be justified by our assumption which confuses us with conflicting explanations as applied to the photoelectric phenomena. The electromagnetic theory fails to adduce a solution to the phenomenon of the expulsion of photoelectrons at the instant a flash of light becomes incident upon material surfaces. We have to refer to

Einstein's equation, supported by the quantum theory, to find an adequate account for the effect.

We can not neglect, however, the importance of the two fundamental tenets assigned to the electromagnetic theory in that, First, *an accelerated charge must radiate*, and Second, *the wave trains of the radiation energy must be continuous*. That is, the emission of energy from the radiating source should produce a continuous wave-front with an intensity varying in accordance with the *inverse square law*.

The velocity of propagation of an electromagnetic wave train may be computed by the following relation:

$$v = \frac{C}{\sqrt{\mu D}} \quad (3)$$

where, v is the velocity of the wave train, C is the ratio of the electrostatic to electromagnetic charges (equal to 2.9979×10^{10} cms. per second), μ and D are respectively the permeability and the dielectric constants of the medium traveled. But, for empty space, these constants are unity, and, therefore, v becomes equal to C .

All wave phenomena of electromagnetic character become related, then, to each other by the equation

$$\lambda = \frac{C}{f} \quad (4)$$

where, λ is the wave-length of the radiation, C is its velocity, and f is the frequency with which the radiation propagates. The relation holds for any electromagnetic wave form from the longest, the electric waves, to the shortest, the cosmic rays.

In Table I, the ranges of electromagnetic waves are given in the order of increasing wavelengths.

To measure the wave lengths of short electromagnetic waves such as x-rays it is more convenient to use the *x-unit*, which is one-thousandth of an *Angstrom unit* (*A. U.*).

The methods by which the detection and measurement of different electromagnetic waves become possible are varied from a cloud chamber method to resonance principles. The higher the frequency of an electromagnetic wave, the more difficult and more complex becomes the measurement of its wavelength.

TABLE I:—THE RANGE OF ELECTROMAGNETIC WAVES

<i>Type of Rays</i>	<i>Wavelengths</i>	<i>Frequencies (Approx.)</i>
Cosmic Rays	.00008 - ? A.U.	3.75×10^{22} cycles/sec.
Gamma Rays	.004 - 1.4	7.5×10^{20} - 2.14×10^{18} "
X-Rays	.06 - 1100	5×10^{19} - 2.72×10^{15} "
Ultra-Violet Rays	136 - 3900	2.3×10^{16} - 7.7×10^{14} "
Visible Rays	3900 - 7700	7.7×10^{14} - 4.0×10^{14} "
Infra-Red Rays	7700 - 4×10^6	4×10^{14} - 7.5×10^{11} "
Hertzian Waves (short)	10^6 - 10^{11}	3×10^{12} - 3.0×10^7 "
Radio Waves	10^{11} - 3×10^{14}	3×10^7 - 10^4 "
Electric Waves	3×10^{14} - 1.2×10^{17}	10^4 - 25 cycles/sec.

However intricate or difficult it may be, the present methods devised for the measurement of extremely short wavelengths give results with accuracy within a millionth fraction of one.

6. Relativity Relation of Mass and Energy.—James Bradley (1692-1762), in his systematic observations of the seasonal displacement of a certain star in the zenith, discovered that the shift in the position of this star was due to the motion of the earth in relation to the velocity of light from the star. The full significance of this phenomenon was not realized until many years later when further investigations of the effect led to the theory of relativity proposed by Albert Einstein in 1905.

The general principle of the theory assumes an unbiased association of equivalence between accelerated and gravitational motions, and denies the existence of any absolute velocity. This consideration further maintains that an accelerated body acquires an increase in mass in measure with its increased energy. On the principle of equivalence of mass and energy, the relation of the change of energy, ΔE , of the moving body due to its velocity v may be expressed as

$$\Delta E = \Delta mc^2 = m_0 c^2 \left[\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1 \right] \quad (5)$$

where, the term in the brackets represents the relativity correction, and in which equation m is the mass of the moving body,

m_0 its rest mass, and c is the velocity of light. When $v = 0$, the corresponding energy reduces to m_0c^2 . Hence, a body at rest contains an energy determined by its rest mass; and, owing to the magnitude of c^2 , the energy for even a small mass is enormously high.

On the assumption of the electromagnetic origin of the electron mass, Sir J. J. Thomson later showed experimentally that there is measurable increase in the mass of an electron when its velocity approaches that of light, a fact that was to be expected on the basis of relativity law. Lorenz further computed independently that the variation in the mass of an electron moving with a velocity v could be given as

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (6)$$

which is an exact picture of what the relativity requirement of the variation of mass with velocity exhibits, and for our purpose, we shall not attempt to go further to explain other aspects concerning relativity, as to present a complete treatise on the subject will cover more space than the aim of this book is concerned with, and in view of the existing excellent textbooks treating the subject more completely from both mathematical and physical standpoints.

7. Summary—The foregoing syllabi represent an attempt in the sketching briefly of the preliminary physical phenomena underlying the principal scope of this textbook. It will be noted that endeavor is made to inter-relate one group of phenomena with that of others in the consideration of mass and energy in relation to electromagnetic and relativistic phenomena. We have seen that mass and energy are interconvertible, and that the magnitude of each of these entities varies with velocity at upper limits on the precept of relativity. Therefore, we shall presently return to these subjects and attempt to present a detailed discussion of some of the phases of importance leading to a thorough grasp of the radiological principles and their applications particularly in industry, for which this book is principally devoted.

CHAPTER II

DYNAMIC CURRENTS

PART I

The Atom and Electricity

1. **A Summary of Atomic Theory.**—As was stated on a previous occasion, the character of matter may be taken as one being of corpuscular behavior and that transformation from one form of matter into another is possible without the destruction of the material particles entering into this structural transition. As early as 1000 B.C., a Hindu chemist, Kanada, had proposed that “things dancing in the hot sun” were “*atoms*,” and that they were “discrete, discontinuous, indivisible, indestructible, and imperishable, but separable by space.” The doctrine foreshadows the modern concept relevant to the laws of conservation. Recent findings disclose, however, that though the atom is the smallest structural form of matter that can bring about a chemical reaction the ultimate of matter by no means resides in this unit structure. An atom is further divisible into *alpha-particles*, *neutrons*, *protons*, *electrons*, *positrons*, and a few other entities of characteristics not fully understood as yet. Nevertheless, it is of no little consequence that the imaginative power of the early scientist could extend sufficiently far as to postulate the indestructibility of matter regardless of operations executed, despite the limited use and application of the then existing apparatus.

On the basis of the representative structure of matter, such as oxygen, nitrogen, copper, iron, etc., its ultimate entity is conserved in the *atom*, which is the smallest representative structural unit of a given matter, exhibiting all the characteristics of the latter as the precursor. In our discussion of the atomic structure, it will be more expedient to assume an atom model of a state having no motion and segregate of external influences of any character. In such a state, the atom will possess definite physical and chemical characteristics.

According to Rutherford's nuclear theory, the essential mass of the atom is concentrated in its *nucleus*, which contains positively

charged particles known as *protons*, and is surrounded by concentric orbits bearing negative charges called *electrons*. The nucleus of the atom contains as many protons as there are electrons in the whole atom. Thus, an atom in the stationary (normal) state is electrically neutral due to the interaction of the electrostatic field between the protons and the electrons.

In an atom, some of the electrons are in the nuclear region and are called the *nuclear electrons*, while the rest of the electrons occupy, in definite numbers, specific atomic orbits and are known as *extranuclear* or *orbital electrons*. Approximately half of the total number of electrons are located in the nucleus and the other half in the orbits. The nuclear electrons by interaction with an equal number of protons constitute the same number of *neutrons*, since the charge on the electron is same in magnitude as the charge of the proton. A neutron, then, is a neutral entity consisting of an electron and a proton occupying the nucleus.

An atom may dissociate to form an equal number of negative and positive charges, which are then known as *ions*. Such a dissociation occurring under favorable conditions whereby a flow of electric charge is produced constitutes the origin of electricity. In metallic conductors, however, the electrons are projected at comparatively great distances from the nuclei of the atoms. These electrons are called "*free electrons*," which occupy the space between the adjacent atoms and are shared by random atoms at random intervals. They are easily removed from the parent atom, or atoms, under the attraction, or repulsion, of an electrical force external to the atom. Under these conditions the electron will acquire an average velocity of drift in the direction of the electric force (voltage) gradient, thus producing a current of electricity. The force which causes the migration of electric charges in a conductor is known as the "*electromotive force*, or *electric potential*." Since the electrons bear negative charges it follows that in metals the flow of current is constituted only by the movement of negative charges axially to the conductor.

In an electric generator, under the influence of magnetic fields, there occurs an isolation of the electrons from the atoms at one end of the armature coil and their aggregation at the other end, which condition produces a difference of potential between these two points, which, when brought together to make a contact,

cause a momentary flow of current through the conductor. When the electrical stress between the negative and the positive ends of the conductor (coil) is thus removed, the atoms within the conductor tend to resume their original state by the recombination of the negative and positive charges.

In view of the "free electron" structure of the atoms, substances may be classified as *conductors*, and *non-conductors* or *insulators* in accordance with the number of free electrons they possess. All substances contain free electrons to some extent, and, those that contain a comparatively large number of these electrons are called conductors, while those that are devoid of free electrons, or contain merely a few electrons per given volume, are known as insulators or *dielectric* substances. Conductors are usually of metal and can readily transmit electric current, while non-conductors are fiber, wood, hard rubber, bakelite, mica, ebonite, lucite, etc., and cannot carry any current to an appreciable extent.

2. International Electrical Units of Measurements.—It has been already observed that a dynamic current is constituted by free electrons in motion in the direction of the potential gradient in a conductor (wire). To elucidate the mechanism of electric flow, then, it is essential to account for the fundamental electrical units which directly enter into the generation, conduction, and consumption of electric power in the form of light, as in electric incandescent or fluorescent lamps, in the form of heat, as in the case of electric heaters, ovens, etc., and in the form of mechanical energy as in motors and dynamos.

When electricity is produced by an electric generator, what actually occurs is the dissociation of the electrons in the atoms of the conducting coil or wire by the influence of the magnetic field surrounding the coil. The purpose of the magnetic field is to induce an electromotive force (motive force behind the electron) to cause the free electrons in the metal (coil) to move along the conductor. But, the path of the free electrons is intercepted by the presence of the metallic atoms which offer a form of "frictional" resistance to the movement of the electrons, and, therefore, the energy to overcome this resistance in producing a flow of current must be supplied in the form of electric potential from the magnetic field. Hence, in the generation of electric

currents, the production of an electromotive force precedes the current flow.

Frequently reference is made to the velocity of electric current as being same as that of light—three-hundred million meters per second. This does not imply, however, that the electrons cover a distance of three-hundred million meters in one second. It merely means that when an electric switch is turned on to cause a flow of electricity through a wire, for instance, three-hundred million meters long, the electrons will begin to issue at the opposite end of the wire within one second. In other words, it is the electron wave set up by the application of a potential between the two ends of the wire conductor that is transmitted from one end to the other and not the electrons that travel at the rate of three-hundred million meters per second. The velocity of the sustained electron flow, however, is dependent upon the magnitude of the applied electric potential and upon the resistance of the medium conducting this current. In a household lighting circuit, for instance, the average velocity attained by the electrons flowing in the wires is of the order of several centimeters per second.

The electrical factors that enter into the production and transmission of a current are the *voltage*, *amperage*, and the *ohmage*. The voltage is the electrical pressure or the electromotive force behind the flow of current which is known as the amperage. The current in its passage through a conductor encounters an interatomic "frictional" resistance which is termed the ohmage. This resistance has to be overcome before a flow of current occurs. The energy required just to overcome this resistance becomes transformed into heat, which energy may be measured in *joules*. If one joule of energy is produced or consumed by an electric current in one second, the relation is referred to as the *wattage*, or the *power*.

Based on the c.g.s. (centimeter-gram-second) system, the definitions of the practical electrical units may be summarized as follows:

- (a) *Ampere*: An ampere is the rate of electric current flow, and when passed through a standard silver nitrate solution it deposits silver at the rate of 1.118 milligrams per second.
- (b) *Coulomb*: A coulomb is the quantity of charge ($6.3 \times$

10^{18} electron charges) carried by a current of 1 ampere in 1 second. $Q = It$.

- (c) *Ohm*: An ohm is a unit electric resistance offered to the passage of current through a column of mercury of constant cross-section, 106.3 centimeters long, at 0°C ., and having a mass of 14.4521 grams.
- (d) *Volt*: A volt is the unit electromotive force or electric potential to overcome a resistance of 1 ohm in a conductor carrying a current of 1 ampere.
- (e) *Watt*: A watt is the unit of power generation or power consumption. It is the rate of work done by 1 volt in driving a current of 1 ampere in 1 second.

Frequently it is more convenient to express the electrical units in terms of their multiples or submultiples. Thus, one *milliampere* means one-thousandth of an ampere; one *micro-ampere* is equal to one-millionth of one ampere. One *kilovolt* (which term is generally used in radiography) is equal to one thousand volts; and, one *megohm* is one million ohms. One *kilowatt* is equal to one thousand watts.

3. Ohm's Law.—When there is a steady flow of electric current in a conductor, there is always a corresponding quantity of voltage drop in that circuit. This is due to the resistance of the conductor. The higher the resistance of the conducting medium, the higher the voltage drop in the circuit. To compute this fall of potential, Ohm, an early physicist, has formulated the following relation:

When electricity flows through a conductor, the current of transmission varies directly as the electromotive force (voltage) and inversely as the resistance (ohmage) of the transmitting circuit. That is, in a given circuit

$$I = \frac{V}{R} \quad (7)$$

and, $V = IR \quad (8)$

where, I is the current in amperes, V the electromotive force in volts, and R is the resistance in ohms.

Example:—An electric incandescent lamp has a resistance of

160 ohms. What must be the line voltage so that a current of 0.75 ampere may flow through the lamp?

In the problem, we are given,

$$\begin{aligned}I &= 0.75 \text{ ampere.} \\ R &= 160 \text{ ohms.}\end{aligned}$$

and, solving for the voltage, we have

$$\begin{aligned}V &= IR \\ &= 0.75 \times 160 \\ &= 120 \text{ volts. } \textit{Ans.}\end{aligned}$$

4. Electric Power, and Energy; Joule's Law.—Power is defined as the rate of doing electrical work. When a current of one ampere flows through a resistance of one ohm, the power is said to be consumed at a unit rate. The work is given as the product of the current times the voltage for a given time the current is prolonged. The unit of electric power is the *watt*, and the electrical work done in one second is known as one *watt-second* or one *joule*. Since power is only the rate of producing electric energy or work, it follows that work per second is the power, or the number of watts used per second.

It is customary to rate the different electric appliances according to the amount of wattage used per second. For instance, if an incandescent lamp is marked as 50-watts at 110 volts, it signifies that when the lamp is connected in a circuit having a voltage of 110 volts, it will consume 50 watts of power every second. If the time of duration of the current flow is known, and this quantity is further converted into seconds and multiplied by 50, the electrical energy of work done during that time is obtained, and is expressed in joules.

The relation of the electrical work to the practical units may be expressed as

$$W = IVt \text{ watt-seconds, or, joules.} \quad (9)$$

in which, W is the electrical work in joules, and t is the duration of current flow in seconds.

Example:—What will be the electrical work done in 20 minutes if a current of 4.5 amperes flows in a circuit impressed with 120 volts?

We are given: $I = 4.5$ amperes.
 $V = 120$ volts.
 $t = 20 \times 60 = 1200$ seconds.

Putting the equation (9), and substituting the numerical values of the known quantities, we obtain

$$\begin{aligned} W &= IVt \\ &= 4.5 \times 120 \times 1200 \\ &= 648,000 \text{ joules. } \textit{Ans.} \end{aligned}$$

It has been already mentioned that the electrical work in joules may also be expressed in watt-seconds. Since power is the rate of doing electrical work, we may show with the aid of equation (9) that power is equal to the product of the current in amperes and the potential in volts. Thus, from equation (9) we have

$$\begin{aligned} W &= IVt \\ \text{Power} &= \frac{IVt}{t} \end{aligned}$$

$$\text{or,} \quad P = IV \text{ watts} \quad (10)$$

where, P stands for power in watts.

Substituting IR for V , in the equation (10), and equating this for P , we obtain

$$\begin{aligned} P &= I \times IR \\ &= I^2 R \text{ watts.} \end{aligned} \quad (11)$$

This equation is necessarily used in finding the rate of power consumption in any system containing ohmic resistance and thus producing heat. For example, electric lamps, electric heaters, electric ovens and furnaces, etc., all produce heat by consuming current. The latter relation, then, may be used to determine the power both in direct- and in alternating-current circuits. The formula, $P = IV$, however, becomes applicable alternatively with equation (11) in cases where direct-current is employed.

The heating effect of an electric current is manifested in a

variety of electrical appliances, such as in incandescent lamps, pressing devices, electric heaters and furnaces, electric blankets, fuses, etc.

To produce heat by electricity, it is necessary to have a coil of wire offering an appreciable amount of ohmic resistance to the flow of the current. Different metals when drawn into wire form to carry current will have different electrical resistances per given length and diameter. There are on the market many types of wire coils that are manufactured specifically for heating purposes. Some of these materials are commercially known as Chromel, Rezistal, Nichrome, Nickel-Chromium alloy, Tungsten, Tungsten-Osmium alloy, etc. They are sold in wire or ribbon forms. However, one must use discretion in choosing the type of wire most suitable to the particular type of work in hand. For instance, Tungsten-Osmium alloys are employed in the filaments of incandescent lamps of special purpose such as in photography, projection work, and micrographic apparatus, where intense light and comparatively long life of the filament are of essential concern. Nichrome is used in household heating units, and Tungsten is generally employed for making the filament of ordinary lighting lamps and for the cathode filaments of rectifiers, x-ray tubes, and radio tubes, owing to the superior property of Tungsten which has low vapor pressure, and high melting point; and, when used as an electron emitting filament, pure Tungsten produces more consistent thermionic current than its alloys or any other metal in the category.

An electric circuit must be protected from an overload and also from a short circuit. Such a protection is achieved by means of electric *fuses*. An electric fuse is a safety device essentially consisting of a strip of metal of predetermined thickness and width, and which by virtue of its low melting point breaks the circuit when the current in the circuit momentarily becomes greater than the fuse is rated to carry. Ordinarily, a *fuse strip* or *link* is made of an alloy of Lead and Tin, or of pure Zinc, Aluminum, etc., any of which melts at relatively low temperature. The link is enclosed in a cartridge or in a plug receptacle which is screwed in a socket in the fuse box provided for the purpose. Fuses are connected between the source of current and the circuit in which the current is to be employed.

Experimental determinations conducted by an English physicist, Joule, and his observations announced in the year 1847, have conclusively indicated that when a current I runs for t seconds in a circuit having a resistance R , and producing energy W , doubling the current quadruples the heat energy. This means that the heating effect of the current varies as the square of the current value. Expressing this relation in an equation form, we obtain

$$W = I^2 R t \text{ joules,} \quad (12)$$

in which, W is the heat energy in joules, and the corresponding values of the quantities in the right-hand term are conserved.

Heat energy is generally measured in *calories*. A calorie of heat is the work done by 4.184 joules, which quantity is equal to 4.184×10^7 ergs. It is the amount of heat required to raise the temperature of one gram of water one degree centigrade. The heat energy H , then, may be given as

$$H = \frac{1}{4.184} \times I^2 R t \text{ calories.} \quad (13)$$

or,

$$H = 0.239 I^2 R t \text{ calories.} \quad (14)$$

Example:—A current of 6 amperes runs for three minutes through the heating coil of an electric toaster having a resistance of 20 ohms. (a) Find the voltage of the circuit. (b) Find the power consumption. (c) Determine the heat energy in joules. (d) How many calories of heat will be produced in the system?

We are given: $I = 6$ amperes.

$R = 20$ ohms.

$t = 3 \times 60 = 180$ seconds.

(a) From equation (8), we have

$$\begin{aligned} V &= IR \\ &= 6 \times 20 \\ &= 120 \text{ volts. } \textit{Ans.} \end{aligned}$$

(b) The power in the circuit may be determined by equation (11) as

$$\begin{aligned}
 P &= I^2 R \\
 &= 6^2 \times 20 \\
 &= 720 \text{ watts. } \textit{Ans.}
 \end{aligned}$$

- (c) Heat energy in joules can be found by equating the equation (12), and substituting the corresponding numerical values as given above.

$$\begin{aligned}
 W &= I^2 R t \\
 &= 6^2 \times 20 \times 180 \\
 &= 129,600 \text{ joules. } \textit{Ans.}
 \end{aligned}$$

- (d) The number of calories produced in three minutes can be calculated from equation (13) or (14).

$$\begin{aligned}
 H &= 24 I^2 R t \\
 &= .24 \times 129,600 \\
 &= 31,104 \text{ calories. } \textit{Ans.}
 \end{aligned}$$

5. Electric Measuring Instruments.—(a) *The Ballistic Galvanometer*.:—One of the simplest and most sensitive mechanically operated electric measuring devices is the D'Arsonval ballistic galvanometer, Fig. 1. It is a direct current measuring device and

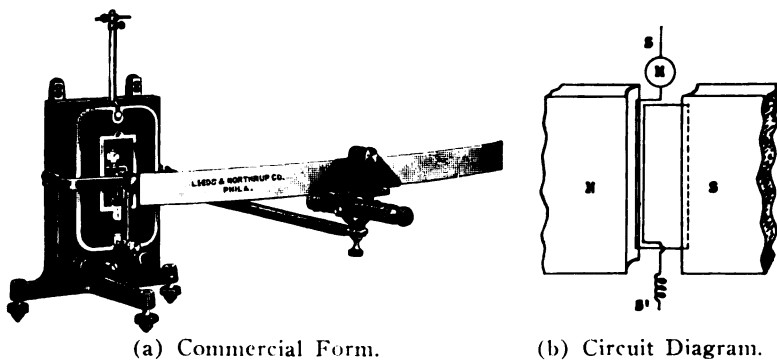


Fig. 1. The D'Arsonval Ballistic Galvanometer.

consists of a moving coil of fine insulated wire suspended between the north and south poles of a permanent magnet and carries the current to be measured. The suspensions S and S' , Fig. 1b, above and below the coil constitute the leads for the incoming

and outgoing current through the instrument. A mirror, *M*, connected to the upper suspension, rotates with the coil when the latter deflects as a result of a flow of current through it, and which current causes the coil to become an electromagnet. Consequently, two opposing magnetic forces are set up between the poles of the permanent magnet and the current-conducting coil. These forces cause the coil to rotate or deflect, since the magnetic poles of the permanent magnet are stationary. The magnitude of the deflection is directly proportional to the amount of current or charge passing through the coil. By means of a scale and telescope arrangement placed about 50 cms. from the mirror, readings are conveniently taken.

The sensitivity (response to small current or charge) of such an instrument varies from 10^{-3} to 10^{-12} ampere per millimeter of scale deflection. This property of the instrument makes it very useful in the measurement of currents of very short durations through the x-ray tube, in accurate determination of resistances of different conductors, and in finding the electrical insulation powers of various dielectric materials. A very elegant method of employing the galvanometer resides in measuring resistances by Wheatstone bridge circuit, while the Kelvin double-bridge method is essentially an improvement on the former.

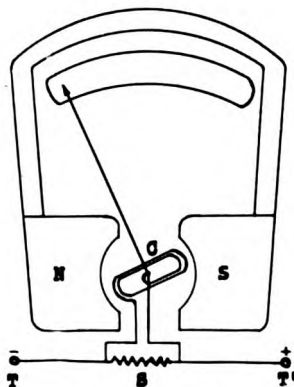
(*b*) *The Ammeter*:—An ammeter is a portable galvanometer of modified form, and is used to measure the current in amperes. The essential components of an ammeter consist of a moving coil of fine insulated wire wound around an aluminum frame which is placed in the magnetic field of a horse-shoe type permanent magnet, and is supported on jewel bearings balanced with restoring springs from the upper and lower side of the coil. A pointer is attached to the aluminum frame and is actuated by the deflection of the coil, indicating on a scale arrangement on the face of the instrument the amount of current passing through the meter. Fig. 2a represents a commercial form of the ammeter, while Fig. 2b is the schematic circuit diagram of the meter.

In Fig. 2b, the moving coil *C* of the instrument is mounted between the two poles, marked by *N* and *S*, of a permanent magnet. Since the moving coil is too delicate to carry currents for instance, of greater magnitude than 20 milliamperes, a low resistance strip *S*, called a shunt, is connected across the coil and

carries most of the current through the instrument by way of the binding posts T and T' . The deflection of the coil, accomplished by the current flowing in the coil, is proportional to the total current passing through the instrument, and varies inversely as the ratio of the resistances between the moving coil and the shunt. That is, if an ammeter reads full scale 10 amperes, and if 0.01 ampere flows in the coil and 9.99 amperes through the shunt, then the ratio of the resistance in the coil to that in the shunt should be 999 : 1.



(a) A Commercial Form of the Ammeter.



(b) The Schematic Diagram of the Ammeter.

Fig. 2. The Ammeter.

In use, an ammeter is always connected in series with the circuit so that it carries all the current that is running through the circuit in which it is connected. For measuring a relatively small current such as that which flows across an x-ray tube, a *milliammeter*, whose scale is calibrated to one-thousandth of an ampere, is generally used.

(c) *The Voltmeter*.—To measure the difference of electrical potential between the two points of a circuit, a device, known as a voltmeter, is used. The voltmeter measures the voltage directly. As in an ammeter, a voltmeter has a moving coil which has a pointer attached on its face, and when a current runs through this coil it deflects in accordance with the current intensity. This current through the coil is very small since there is a high resistance connected in series with it. Unlike an ammeter, a voltmeter does not have a shunt. Therefore, the total current of the meter, which

is of the order of a few milliamperes, passes through the coil.

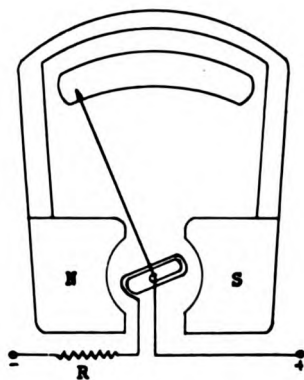
Owing to the high magnitude of the series resistance of the voltmeter coil, the instrument can be connected, without becoming damaged, directly across the source of the current, provided that the voltage range of the meter is not exceeded. Fig. 3b, below, illustrates the circuit diagram of a voltmeter, while Fig. 3a is a commercial form of the device.

As mentioned above, the deflection of the moving coil of a voltmeter is proportional to the current passing through it, and hence, when the instrument is properly calibrated it indicates the potential in volts, as, according to Ohm's Law, the potential indicated by the instrument is equal to the product of the resistance and the current through it.

At present, there are various types of voltmeters used for a



(a) A Commercial Form of the Voltmeter.



(b) Schematic Diagram of the Voltmeter.

Fig. 3. The Voltmeter.

number of different voltage measuring purposes. Among them, the moving coil voltmeter is used for ordinary voltage ranges; the vacuum tube voltmeter is used for detecting and amplifying extremely small current impulses, or charges; and, the electrostatic voltmeter and the sphere-gap voltmeter are used in measuring the voltage of high tension circuits such as employed in x-ray apparatus, radio transmission circuits, nuclear transmutations, experimental work, etc.

(d) *The Wattmeter*.—The wattmeter is an instrument which

indicates the amount of power consumed in watts. The device consists of a combination of a voltmeter and an ammeter circuit connected in series-parallel so as to produce a deflection of the pointer proportional to both the voltage and the current. The wattmeter is always connected between the mains and the load to be measured. A modification of the wattmeter is the watt-hour meter, which registers the electrical energy used in watt-hours, or, its multiple, in kilowatt-hours.

6. Fundamentals of Electric Circuits.—In order to acquire a comprehensive knowledge of the electrical units and their relation to each other in a given circuit, it will be appropriate here to present the several fundamental circuits to which all other circuits are related. That is, any electrical circuit, regardless how complex it may be, is a modification of one or a combination of these fundamental circuits and is directly dependent on the character of their arrangements. All such modifications may be reduced to the simpler and basic circuits in making an attempt to trace the current or in determining the values of the different electrical quantities entering into the circuit relation.

(a) Measurement of Resistance by Ammeter and Voltmeter Method:—In Fig. 4, below, a resistance R is connected across a battery B through an ammeter A and a switch S . A voltmeter V is connected across the two terminals of the resistance R . When the shunt switch S is closed, a current I flows through the resistance R and the magnitude of this current is indicated by the ammeter. The latter is connected in series with the resistance R ,

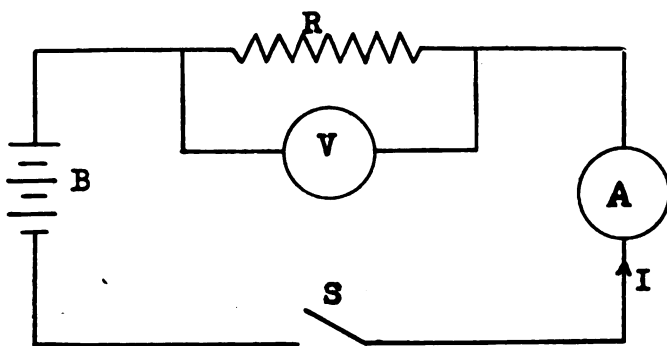


Fig. 4. Circuit Diagram Showing the Connection of the Voltmeter and the Ammeter in the Measurement of a Resistance.

and therefore, the same current that flows into R passes through the ammeter A .

If readings of the voltmeter and the ammeter are taken and then R is equated against the voltage and the amperage, we obtain $R = V/I$, as from Ohm's Law the voltage drop across a given resistance is equal to the product of the resistance and the current flowing through it; that is, $V = IR$.

This method of measuring the resistance of any given circuit is the simplest and the most common, though the scheme offers certain limitations, since in order to obtain very accurate results by this method the resistance to be measured should not exceed 25% of the resistance of the voltmeter. Furthermore, the voltmeter shown in Fig. 4 reads the voltage across the resistance but the ammeter reads the combined current through the voltmeter and the resistance. On the other hand, if the voltmeter is connected across the ammeter and the resistance together, the true voltage drop read by the voltmeter will not be that across the resistor. Consequently, this method, though it will give reasonably accurate results for ordinary purposes, should be used with discretion.

(b) *Measurement of Equivalent Resistance of Resistors Connected in Series:*—The equivalent resistance of a number of resistors connected in series is equal to the algebraic sum of the individual resistors. In Fig. 5, let R be the equivalent or total resistance of the resistors r_1 , r_2 , and r_3 . The current through each of the three resistors is same and is designated by I . E is the voltage of the battery furnishing the current to the circuit.

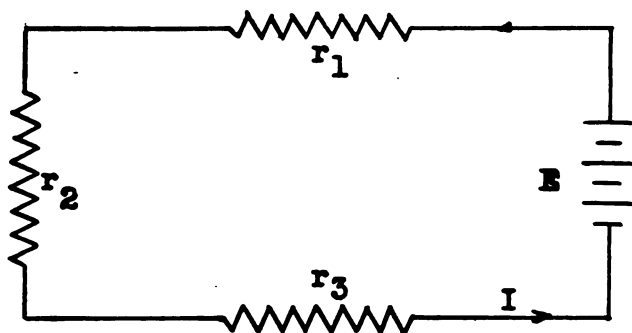


Fig. 5. Resistances Connected in Series.

According to Ohm's Law, the fall of potential across r_1 is $Ir_1 = E_1$, across r_2 is $Ir_2 = E_2$, and that across r_3 is $Ir_3 = E_3$. The sum of all the three individual potential drops is E . Hence, the total potential fall is given as

$$E = E_1 + E_2 + E_3 \quad (15)$$

$$E = Ir_1 + Ir_2 + Ir_3 \quad (16)$$

but, $E = IR$, where, R = total resistance, and I = current through the circuit.

By substituting, therefore, IR for E , and isolating I from each term on the right hand side of equation (16), we have

$$IR = I(r_1 + r_2 + r_3)$$

and, dividing both sides of the equation by I , we obtain

$$R = r_1 + r_2 + r_3 \quad (17)$$

We may, therefore, state that when resistances are connected in series, the total voltage drop across the circuit is equal to the sum of the individual voltages, and that the equivalent resistance is equal to the sum of the individual resistors, the current through the latter being constant.

Example:—Three electric lamps having resistances respectively 15 ohms, 20 ohms, and 25 ohms are connected in series. If the current through the circuit is 2 amperes, (1) What will be the potential drop of the individual lamps? (2) What will be the total resistance of the circuit? (3) Find the total potential across the circuit.

We are given: $r_1 = 15$ ohms.
 $r_2 = 20$ ohms.
 $r_3 = 25$ ohms.
 $I = 2$ amperes.

(a) The potential drop across r_1 is

$$\begin{aligned} E &= Ir_1 \\ &= 2 \times 15 = 30 \text{ volts. } \textit{Ans.} \end{aligned}$$

The voltage across r_2 is

$$E_2 = Ir_2 = 2 \times 20 = 40 \text{ volts. } \textit{Ans.}$$

The voltage drop across r_3 is

$$E_3 = Ir_3 = 2 \times 25 = 50 \text{ volts. } Ans.$$

(b) The equivalent resistance of all the lamps will be

$$\begin{aligned} R &= r_1 + r_2 + r_3 \\ &= 15 + 20 + 25 \\ &= 60 \text{ ohms. } Ans. \end{aligned}$$

(c) The potential across the whole circuit is

$$\begin{aligned} E &= E_1 + E_2 + E_3 \\ &= 30 + 40 + 50 \\ &= 120 \text{ volts. } Ans. \end{aligned}$$

(c) *Measurement of Equivalent Resistance of Resistors Connected in Parallel:*—If several resistances, such as r_1 , r_2 , r_3 , etc., are connected to a current source so that each resistance receives the same voltage from the source E , they are said to be in parallel connection. The current in each resistive circuit will be inversely

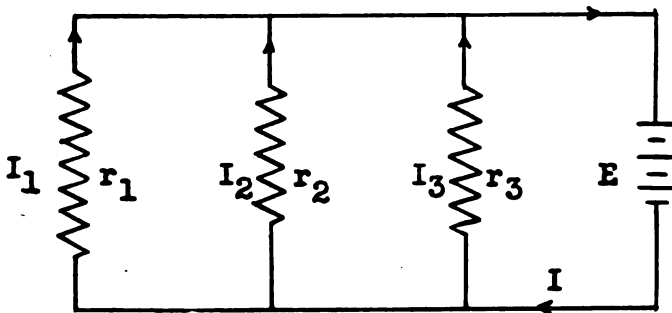


Fig. 6. Resistances Connected in Parallel.

proportional to the value of its resistance so that the product of the current and the resistance in the individual branch circuit will be equal to the impressed voltage E .

By Ohm's Law, the current I_1 through the resistance r_1 is E/r_1 ; I_2 through r_2 is E/r_2 ; and, the current I_3 through the resistance r_3 is E/r_3 .

The total current I through the whole circuit is the sum of the currents through the individual paths. Hence, we have

$$I = I_1 + I_2 + I_3 \quad (18)$$

Substituting the corresponding voltage and resistance values of the individual currents in equation (18), we obtain

$$I = \frac{E}{r_1} + \frac{E}{r_2} + \frac{E}{r_3} \quad (19)$$

but, the total current I is equal to E/R , where R is the equivalent or total resistance of the parallel circuits. Hence, we may equate

$$E/R = E(1/r_1 + 1/r_2 + 1/r_3) \quad (20)$$

Cancelling E from each side of the equation, we get

$$1/R = 1/r_1 + 1/r_2 + 1/r_3 \quad (21)$$

From equation (21) it is evident then that the reciprocal of the equivalent resistance of a number of conductors connected in parallel is equal to the sum of the reciprocals of the individual resistances. It will be further noted that the value of the total resistance R is less than any one of the resistances alone.

Example:—Three incandescent lamps respectively having resistances of 40, 60, and 120 ohms are connected in parallel across a 120 volt current source, as shown in Fig. 7.

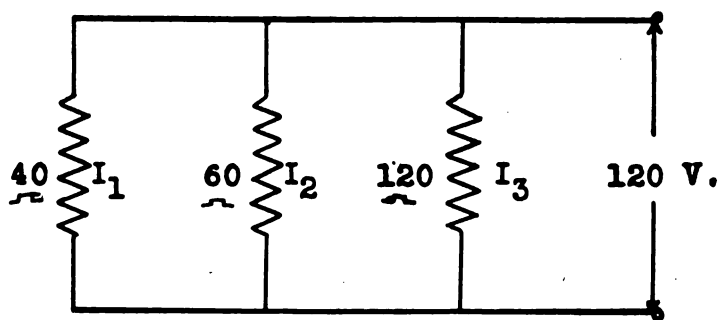


Fig. 7. Resistances in Parallel.

(1) Find the equivalent resistance of the system. (2) What will be the current through each branch circuit?

From equation (21), the total resistance of the system may be found by equating

$$1/R = 1/40 + 1/60 + 1/120$$

$$1/R = \frac{3 + 2 + 1}{120} = \frac{6}{120}$$

$$R = \frac{120}{6} = 20.0 \text{ ohms. } \textit{Ans.}$$

(2) The current in each branch circuit will be

$$I_1 = E/r_1 = 120/40 = 3 \text{ amperes. } \textit{Ans.}$$

$$I_2 = E/r_2 = 120/60 = 2 \text{ amperes. } \textit{Ans.}$$

$$I_3 = E/r_3 = 120/120 = 1 \text{ ampere. } \textit{Ans.}$$

(d) *Specific Resistance and Temperature Coefficient*:—As mentioned above, the electrical resistance of a conductor is directly proportional to its length and inversely proportional to its cross-sectional area. That is, the longer a wire carrying current the greater its resistance becomes, and the larger the diameter or the cross-sectional area the smaller is the resistance of that conductor. Expressing these relations quantitatively, we obtain

$$R = \frac{\rho L}{A} \text{ ohms,} \quad (22)$$

where, R is the resistance of the conductor, ρ its specific resistance (also known as resistivity) given in ohms per Cc, A is the cross-sectional area of the conductor in square centimeters, and L is its length in centimeters. The specific resistance of a conductor, then, is the amount of resistance per cubic centimeter of that material at a given temperature, usually 0°C. or 20°C. The value further varies with the character of the conductor and depends on the number of free electrons in the material.

The resistance of a given conductor, however, changes with its temperature, since heat increases the interatomic "frictional" resistance. But, with an insulator or dielectric material, the resistance generally decreases with rise of temperature. Materials, such as sulphur, mica, and glass, while excellent insulators at ordinary temperatures, lose their dielectric power to a certain ex-

tent when heated to a high temperature. For all pure metals, however, the resistance increases with increase of temperature. The change of resistance per degree centigrade is known as the temperature coefficient of that material, and is proportional to the specific resistance of the material. An equation expressing this relation may be given as

$$\rho = \rho_0 [1 + a_0 (T - T_0)] \text{ ohm-cms.} \quad (23)$$

Substituting RA/L for the resistivity, from equation (22), on both sides of equation (23), we obtain

$$RA/L = R_0 A/L [1 + a_0 (T - T_0)] \text{ ohm-cms.} \quad (24)$$

$$\text{or,} \quad R = R_0 [1 + a_0 (T - T_0)] \text{ ohm-cms.} \quad (25)$$

in which, R_0 and T_0 are the original resistance and the temperature respectively, a_0 is the temperature coefficient of resistivity at temperature T_0 , and R is the resistance to be determined at a temperature T . The value of T_0 is usually taken as 20°C. , the room temperature, and therefore, a_0 is the corresponding temperature coefficient at this temperature.

(e) *Electrical Capacitance*:—When two conductors are separated by a layer of suitable insulator, the device is known as an electric *condenser*. A condenser, then, is an apparatus to store electric charge. It generally consists of alternate layers of metal foil and an insulator, and the circuit leads are taken from the two opposite end conductors. Condensers are widely used in producing high frequency oscillations, in filtering rectified currents, in the modulation of radio-frequency waves, etc., both in radio, and in medical diathermy apparatus. A condenser may also be used in connection with an impedance circuit to produce amplification of alternating voltages. This is done by charging a number of condensers in parallel and discharging them in series. In some types of x-ray rectification systems condensers are employed for stepping up the voltage in the secondary side of the x-ray transformer.

In Fig. 8a, the condenser, represented by the plates a and b , is connected across a voltage source V . Upon closing the switch

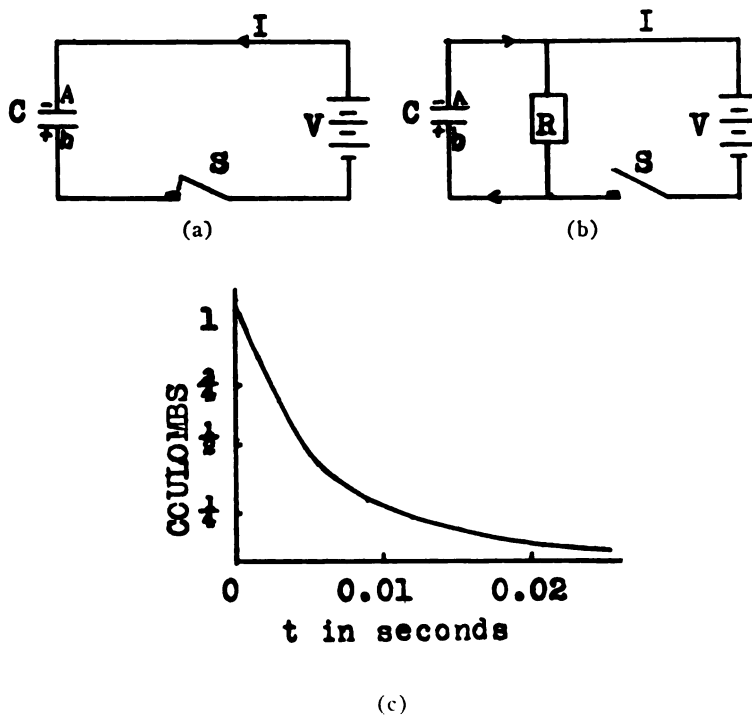


Fig. 8. The Principle of a Condenser Illustrated. In the circuit shown in (a) the condenser is charging; in (b) it is discharging through a load R . Note that the direction of the flow of charge in (a) and (b) are reversed. (c) represents an oscillographic curve showing the manner of discharge of a condenser.

S , a current I flows to the condenser and charges it with the same voltage V of the source, causing a quantity of electricity Q to be accumulated on the condenser plates. If C is the capacity of the plates to hold electric charge, then the amount of charge Q accumulated on the plates of the condenser may be calculated from the formula

$$Q = CV \text{ Coulombs} \quad (26)$$

where, C is the capacitance of the condenser in farads, and V is the applied potential in volts on the condenser.

If the switch S , in Fig. 8b, is opened, and a conducting material such as copper wire of resistance R is connected across the con-

denser, the discharge will occur at a rate dependent on the value of the resistance.

An arrangement consisting of a condenser and a variable resistance in connection with amplifiers and relays is used to time the exposure techniques of relatively short durations. Such a device is known commercially as an *impulse timer*.

PART II

Direct and Alternating Currents

A current whose intensity and direction of flow remain constant with the duration of the flow is known as *direct* or *constant current*. In a current of this character, then, the electron wave is unidirectional and in the same directional phase as the impressed negative voltage gradient. The magnitude of the free electron displacements, having a direction of motion from the negative pole to the positive pole, does not change throughout the duration of the current flow. Hence, when the circuit in a direct current system is closed, there is a short time lag during which interval the current builds up to a maximum, and continues at the maximum value until the circuit is opened.

In the case of an alternating current, the free electrons are displaced periodically to and fro axially to the conductor. That is, there are reversals of direction in the displacement of the free electrons during every second. Hence, an alternating current is constituted by the systematic vibrations of the electrons axially along the conductor without a continuous flow of electrons. Usually, these periodic changes occur 50 times, 100 times, and 120 times per second in an ordinary lighting circuit.

1. Generation of An Alternating Current.—If a coil of wire *C*, in Fig. 9, is rotated on its axis *X-X'* in the magnetic field of the two magnetic poles *N* and *S*, an alternating electromotive force will be induced between the two terminals of the coil. These terminals are further connected to slip rings *R* and *R'*. As the coil is made to rotate continuously in one direction, the voltage and the current thus generated will each change its direction twice during each complete revolution of the coil. This reversal of direction of the current flow is due to the change of direction of

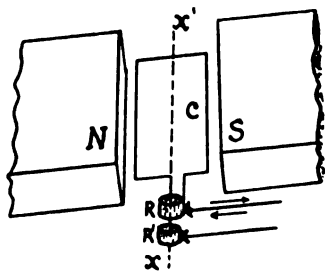


Fig. 9. Production of an Alternating Current.

the magnetic lines of force cut by the wire conductor. For instance, when the coil side adjacent to *C* in the figure cuts lines of force in the immediate vicinity of the south magnetic pole, the induced *EMF* or voltage will have a direction opposite to that when the same portion of the coil cuts lines of force near the north pole. Consequently, the induced current, or, the *EMF*,

will change its direction each time the same side of the conductor approaches a magnetic pole. Such a system consisting of a magnetic field and a rotating coil of wire placed in the field constitutes a simple electric generator. An ordinary A. C. generator consists of a large number of these coil conductors forming the rotor, or, the armature, rotating in the stationary magnetic field of the generator poles. High capacity alternating current generators are generally made of stationary conductors and a revolving magnetic field.

Alternating currents offer the advantage of being generated at low voltages and transmitted at high voltages at comparatively low cost of equipment and maintenance. Such a property of the current affords the production of electrical energy in large quantities in a single station, and its distribution over a large territory.

At present, alternating currents are generated for distribution at voltages varying from 2,200 to 16,500 volts, depending on the capacity of the generator and the territory to be supplied. Since the transmission of electric power can be accomplished most efficiently only by use of high voltage, the power from the generating plant is first impressed on a transformer of large capacity to step up the voltage to any desired value. Alternating current is usually transmitted at the highest possible voltage consistent with the transmission facilities and the distance to which the power is to be carried. Voltages as high as 85,000 volts, and in some localities 250,000 volts, are employed in the transmission. At the latter voltage the power can be distributed within a radius of hundreds of miles with only negligible loss of power.

The high voltage of transmission is brought to substations where

the voltage is reduced to 125, 250, 440, or 550 volts before the power is supplied to the city community. For lighting and other household appliances usually a 125-volt current is used, and for a factory, or large polyphase motors, voltages from 220 volts to 550 volts are used. Because an alternating current can be converted easily and at a high efficiency from a current of one available voltage into any other desired voltage, it is now in general use.

Alternating current generators are built in larger units, having high speeds, and the power cost per kilowatt-hour is low. Since the speed of an A. C. motor is dependent upon the *frequency* (periodic change of direction) of the current, which frequency being constant for a given current, a constant speed work is thus made possible. In a laboratory, or in a factory, where uniform speed is of primary concern, usually induction, or, synchronous, motors are used because of their being more suitable for constant speed work.

2. The Sine Wave of An Alternating Current.—In Fig. 10, an isolated coil from the armature of a generator is placed in the magnetic field of the poles marked by *N* and *S*. The coil side *R* at position marked by *A* is in a comparatively neutral zone and therefore is cutting only a few lines of force, or none at all. But, as it moves toward the north pole of the field magnet, the lines of force threading the coil increase in number, and when the coil reaches the position *B*, the magnetic lines cut by it become a maximum. The coil at this position is said to have rotated 90 electrical degrees. As the coil continues to move toward *C*,

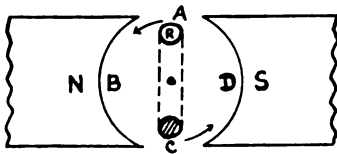


Fig. 10. Alternating EMF Produced in a Coil of Wire.

the magnetic lines of force influencing it will decrease in number, and the coil will have traveled 180 electrical degrees. Hence, the induced *EMF* in the coil will be a maximum at *B*, and a minimum or zero at *C*.

Similarly, as the coil travels from *C* through *D* to *A*, the magnetic lines of force gradually increase to a maximum at *D* and back to a minimum at *A*. The coil, then, has made a complete rotation of 360 electrical degrees, during which time the induced *EMF* has reached twice each of a

maximum value and a minimum value, and its direction is reversed only once. The current thus has made a complete *cycle*.

It is then apparent that each time the current value reaches a maximum and back to a minimum, the current is said to have made one *alternation*. Therefore, when the armature coil has moved through 180 electrical degrees, the current has made one alternation or one-half cycle; and, when the coil moves through 360 electrical degrees, the current makes one complete cycle. A 50-cycle current, then, alternates (changes its direction) 100 times per second, and a 60-cycle current alternates 120 times per second. In general, alternating currents for lighting circuits are transmitted at 25, 50 and 60 cycles per second.

Fig. 11 represents the graphical form of a complete cycle, and is called the *sine-wave* of the current, or, the potential. The sine wave of an alternating current indicates the instantaneous values of the current, or, the potential, intensity through the coil of the generator armature at any electrical degree of its rotation. Since

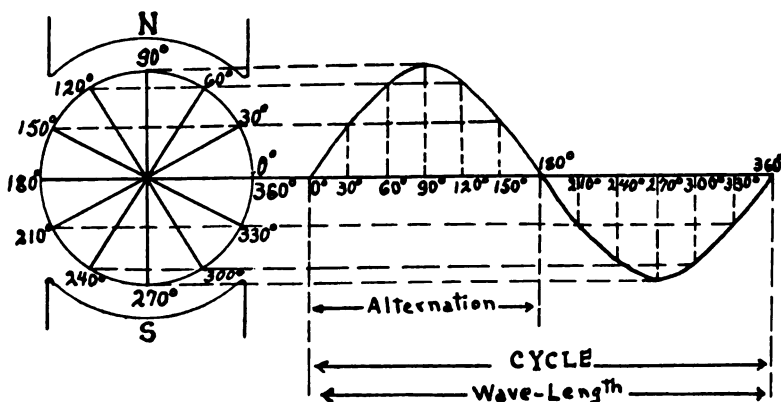


Fig. 11. The Sine Wave of an A. C.

the wave curve of an alternating current of the above form is plotted by the sine of the successive electrical time angles covered by the armature coil in respect with two successive unlike magnetic poles of the generator, and hence the corresponding change in the magnitude of the induced *EMF*, the curve is generally known as the "*sine wave*" of the current.

As has been already observed, an alternating current moves along a conductor in a wave motion, each wave occurring in a definite interval of time and having uniformly the same length as the one preceding or following it.

Supposing in Fig. 12, the current wave in a given conductor reaches from *A* to *C* in one second, and makes two alternations. The curve *ANBRC* represents one *cycle*, or, one *frequency*, of the

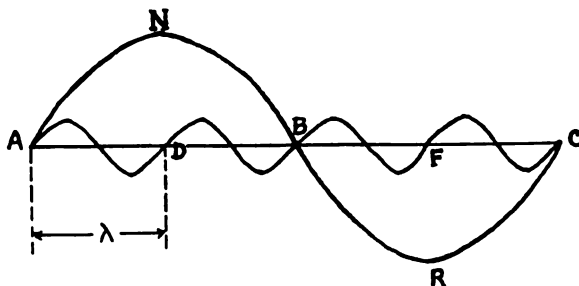


Fig. 12. A Comparison of Alternating Current Waves.

current, and its *wavelength* is determined by the straight line distance between *A* and *C*. Since an electric current wave travels with the speed of light, 3×10^{10} cms per second, the distance between *A* and *C* must then be 3×10^{10} cms. But, this is the distance covered by the current wave in question in one second. Therefore, the wavelength of the current is 3×10^{10} cms, and its frequency is one cycle per second.

Assuming that the above current makes 4 cycles per second, then its wavelength will decrease to $\frac{1}{4}$ th, indicated by the linear magnitude *AD* in Fig. 12. Hence, we can formulate an equation to designate the relation between the wavelength and the frequency of an alternating current as follows:

$$\lambda = \frac{C}{f} \quad (27)$$

and,

$$f = \frac{\lambda}{C} \quad (28)$$

where, *C* is the speed of light, 3×10^{10} cms per second, *f* is the frequency of the current in cycles per second, and λ is the wavelength of the current in centimeters.

It should be noted that the equations (27) and (28) may apply to any electromagnetic radiation. This includes x-rays, ultra-violet rays, visible radiation, infra-red rays, radio waves, and electric waves.

Example:—A certain x-ray radiation has a frequency of 1.5×10^{19} cycles per second. Find its wavelength in angstrom units (A.U.).

By equation (27), we have

$$\lambda = \frac{C}{f}$$

$$\text{where, } C = 3 \times 10^{10} \times 10^8 \text{ A.U.}$$

$$f = 1.5 \times 10^{19} \text{ cycles}$$

$$\lambda = \frac{3 \times 10^{10} \times 10^8}{1.5 \times 10^{19}} = 0.2 \text{ A.U. Ans.}$$

3. The Effective EMF, Current, and Power; the Power Factor.—Any point on the wave curve shown in Fig. 12 represents the instantaneous magnitude of the *EMF* at that amplitude. This amplitude indicated by that point, then, is only the *peak value* of the *EMF* and not the true or *effective value*. The pointer of a volt-meter connected across a circuit of this type of current will not follow the true outline of the voltage wave, but by virtue of the design of the instrument, the pointer will indicate the effective magnitude of the voltage. The effective value, also known as *root-mean-square*, of an alternating *EMF* is then that value which when expended will force an electric flow through a given circuit containing non-reactive resistance with the same rate as that of a direct-current *EMF*.

The effective *EMF* may be given in an equation form as

$$E = \frac{E_m}{\sqrt{2}} = 0.707 E_m \quad (29)$$

where E_m is the instantaneous maximum potential or *EMF* in volts, and $\sqrt{2}$ is the ratio between the maximum and the effective values.

Similarly, the effective value of an alternating current is that value which will develop heat of the same amount in a non-reactive

resistance as that developed by a direct current of the same magnitude. For instance, 1 ampere of effective alternating current will produce the same number of calories in a pure ohmic resistance in a given time as will be produced by a direct current of 1 ampere under identical conditions. The effective value I of an alternating current may be expressed as

$$I = \frac{I_m}{\sqrt{2}} = 0.707 I_m \quad (30)$$

in which, I is the maximum or the peak value of the alternating current.

It should be noted that in giving the value of an alternating voltage or current inference should be made as to whether the values are effective or peak. This indication becomes of especial importance when considering work done in radiography, since older techniques called for the effective value of the voltage, whereas the prevalent exposure techniques at present are generally given in *crest* or *peak kilovoltage*. However, if the available value of the current or the potential is effective, it may be converted into the peak value by multiplying it with 1.41.

The power in an alternating current circuit is the product of the maximum value of the current and the voltage, and, the effective value of this power may be expressed as

$$P = \frac{I_m}{\sqrt{2}} \times \frac{V_m}{\sqrt{2}} = \frac{I_m V_m}{2} \quad (31)$$

where, I_m and V_m are respectively the maximum values of the current and the voltage.

In terms of the effective values of the current and the voltage, the effective power may be written as

$$P = IV \cos \theta \quad (32)$$

in which, $\cos \theta$ is called the *power factor* and is equivalent to the angular difference in electrical degrees between the current and the voltage. In an ordinary power transmission, or when power is expended in a circuit containing only ohmic resistance, this angular difference (*phase angle*) amounts to almost zero. Hence, we may write the relation

$$P = IV = I^2 R \quad (33)$$

where, the two quantities, the current I and the potential V are taken as effective, and R is the resistance of the circuit.

4. Alternating Current Circuit Having Non-reactive Resistance.—In an alternating circuit containing only ohmic resistance, the instantaneous magnitude of the current is equal to the voltage at that instant divided by the resistance of the circuit, since under these conditions the variations in current magnitude keep exact step with the acceleration of the electron flow due to voltage. It is said, therefore, that the current and the voltage rise and fall simultaneously; that is, they are *in phase*. If the values of the current and the voltage are taken as effective, the relation may be expressed by Ohm's Law, $V = IR$. The power expended will be $P = I^2R$.

5. Alternating Current Circuit Having An Inductive Resistance.—In a circuit having an inductive resistance but no ohmic resistance, the current wave lags 90 electrical degrees behind the voltage wave which produces it. The phase angle, then is 90 degrees, the voltage leading the current.

As was mentioned in a previous section, when a current runs in a coil of wire magnetic lines of force are set up around it, and a counter electromotive force (opposing voltage) is produced in the wire, offering a resistance to the flow of current through the coil. This apparent resistance due to the induced back electromotive force is called an *inductive resistance*, and the circuit is known as having an *inductance*.

The effective voltage in an inductive circuit may be given by a formula as follows:

$$E = (2\pi fL)I \text{ volts,} \quad (34)$$

where, f is the frequency of the effective current I , and L is the inductance of the circuit in henries. The quantity in the parenthesis is known as the inductive reactance frequently given by the symbol X_L .

6. Circuits Having Capacitive Resistance.—It has been already shown that the quantity of electricity stored in a condenser connected in a circuit is proportional to the capacity of the condenser to hold charges and to the difference of potential existing between the terminals of the condenser. The current which

charges the condenser will continue to flow as long as the voltage is rising and falling but will become zero as soon as the voltage ceases to change in value. The condenser is charged and discharged twice every cycle, and hence, the current wave is affected through the circuit twice in one direction and twice in the other.

The current in a capacitive circuit leads the voltage by 90 electrical degrees. Accordingly, the phase difference between these two quantities is 90 degrees. The capacitive reactance $1/2\pi fC$ is designated as X_c where more than one reactance occurs in the same circuit.

The value of the current through a condenser circuit is given as

$$I = (2\pi fC)E \text{ amperes,} \quad (35)$$

in which, C is the capacitance in farads, and the values of E and I are effective. The quantity $2\pi fC$ is the reciprocal of the capacitive reactance X_c , which is given in ohms.

7. Capacitance in Parallel Plates.—In building a condenser, consideration is directed to the magnitude of charge which is required of the condenser to retain under given electrical conditions. Together with this information it becomes essential that the dimensions of the plates of the device be known. An equation expressing the relation of the capacitance required to the dimensions of the condenser capable to store the desired electric charge is given below.

$$C = \frac{K.A(N-1)}{4\pi d \times 9 \times 10^{11}} \quad (36)$$

in which, C is the capacitance in farads, N is the number of plates, A is the area of the active surface of the condenser plate and is given in square centimeters, d is the distance between the two adjacent condenser plates, and K is the dielectric constant of the insulating material between the plates. The value of K for air is 1, whereas it is 6 for mica, 4 for glass, 16.5 for diamond, 5.5 for quartz, 3 for shellac, and 2 for paraffined paper.

Example:—A certain condenser, consisting of two plates of tin foil, each 0.002 inches thick, is constructed in the form of a photographic roll-film. If the plates are 30 feet long, 4 inches wide, and separated by an insulating material such as paraffined

paper, what will be the capacity of the condenser? What will be the smallest dimension of the aluminum case into which such a condenser will fit?

The area of each plate whose both sides are active may be calculated as

$$\begin{aligned} A &= 2 \times 30 \times 12 \times 4 = 2880 \text{ sq. in.} \\ \text{or,} \quad &= 2880 \times 6.25 = 18,000 \text{ sq. cms.} \\ d &= 0.002 \times 2.5 = 0.0050 \\ K &= 2 \\ N &= 2 \end{aligned}$$

Therefore, by equation (36), we have

$$\begin{aligned} C &= \frac{2 \times 18,000 \times 1}{4\pi \times 0.005 \times 9 \times 10^{11}} \\ &= 0.64 \times 10^{-6} \text{ farads. } \textit{Ans.} \\ \text{or,} \quad &= 0.64 \text{ microfarads. } \textit{Ans.} \end{aligned}$$

Such a condenser will fit into a casing 4.5 inches deep and 1.25 inches square.

8. Circuits Having Resistance, Inductance, and Capacitance.—For a circuit containing pure resistance with one or two reactive resistances in series, the apparent resistance of the circuit is found by the square root of the sum of the squares of the individual resistances in each reactive circuit. The total resistance in such a circuit is called the *impedance*, designated by the letter Z .

The impedance may be calculated by the vector sum of all the resistances in the circuit. Since the voltage in an inductive circuit is leading the current by 90 degrees while the current in a capacitive circuit leads the voltage by 90 degrees, a phase difference of 180 degrees, the direction of current in the two circuits is opposing, and the resultant potential will be equal to the vector difference of the two potentials. The equation for the total potential across the circuit may be given as

$$E = IZ = I\sqrt{R^2 + (2\pi fL - 1/2\pi fC)^2} \quad (37)$$

9. Three-Phase Y-Connection System.—A three-phase system consists of three individual circuits connected together in

such a manner that the voltages (and the currents) are respectively 120 degrees apart. All three circuits may be generated by a common generator, and each circuit may be employed alone as a single phase line. If the three-phase system has four wires, one of which being the ground wire, the potential of the individual phases may be measured by the difference of voltage between the circuit wire and the ground connection. In such a system the individual phase circuits may or may not be in balance, and when the latter case is met a current will flow in the ground or neutral wire. Such a condition is not desirable. Thus, a three-wire arrangement is usually preferred.

A three-wire three-phase electric system is the general type of polyphase power that is ordinarily used in city transmission lines. Such a system is more economical in cost, and because the individual phase circuits may be balanced, there is no waste of power and each phase line may be operated independently of the other. That is, consumption of a large power in one phase does not affect the power in the other phase or phases to any appreciable degree.

In a Y-connected balanced system, the voltage between the line conductors is given as

$$E = 2E_n \cos 30^\circ = \sqrt{3} E_n \quad (38)$$

where, E is the vector sum of any two conductors of the Y-system, and E_n is the voltage of any one line to ground or neutral wire.

In a balanced three-phase system of Y-connection, the total power may be given as

$$P = 3E_n I \cos \Theta \quad (39)$$

in which, P is the power in watts, E_n the voltage of any one wire to neutral, I the current through the circuit, and Θ is the phase angle.

Since the ratings of transmission lines and the machines in which power is consumed are generally given by the voltage between the phases, we may substitute E from equation (38) for E_n in equation (39) and obtain the expression

$$P = \sqrt{3} EI \cos \Theta \quad (40)$$

where, E is the voltage between the line conductors.

10. Alternating Current Transformers.—The transformer is an induction device which transforms a voltage of one value to one of different value. A simple transformer essentially consists of a soft-iron closed core or frame as shown in Fig. 13, and two independent coils of insulated copper wire wound around each of the two opposite sides of the core. One

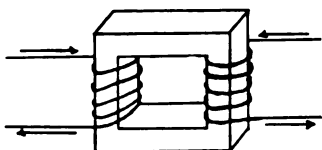


Fig. 13. A Closed Core Transformer.

of these coils is called the *primary coil*, and the other the *secondary coil* of the transformer. Depending as to whether the number of turns of wire in the secondary is greater or smaller than that in the primary, the device becomes respectively either a *step-up* or a *step-down transformer*. If the number of turns of wire in either the primary or secondary are equal then it is called an *insulating transformer*.

A step-up transformer consists of relatively more turns of fine wire in its secondary than in the primary winding, and thus it produces a higher voltage than the voltage applied in the primary. In a step-down transformer, the number of turns in the primary is greater than that in the secondary. The insulating transformer having the same number of turns of wire on either side of the transformer retains a duplicate voltage in the secondary of that applied on the primary coil.

When an alternating current is sent through the primary coil of a transformer, the soft iron core becomes magnetized, and the magnetic flux through it changes its course forward and backward. Consequently, the magnetic field around the core will change in intensity and direction with each alternation of the current through the primary coil. This effect produces, in the secondary coil, an induced electromotive force of the same frequency as that of the current in the primary winding.

The magnitude of the induced voltage in the secondary will depend upon the frequency of change of the magnetic field, and upon the number of turns of the secondary winding. The voltage in the secondary will further vary with the ratio of the number of turns in its winding to the number of turns in the primary winding.

An equation representing the induced electromotive force

(voltage) in the secondary of a transformer may be given as

$$E = N \frac{2\pi f \Phi}{\sqrt{2} \times 10^8} \text{ volts,} \quad (41)$$

where, E is the induced electromotive force in volts having an effective value, N is the number of turns in the winding, f the frequency of the current in cycles, and Φ is the magnetic flux in maxwells (lines of force) through the transformer core. The formula, however, holds only for an alternating current having a sine wave form.

Transformers employed for high power transmission as well as those used in an x-ray machine are usually immersed in a heavy insulating oil, which prevents a possible spark-over from the high tension side of the transformer to some other point, thus obviating the possible destruction of the transformer or its parts. The purpose of the oil is also to cool the low tension winding which carries comparatively large current. Oil-immersed transformers are usually hermetically sealed in an iron or steel container.

Assuming that there are twice as many turns of wire in the secondary winding as in the primary, the induced voltage through the secondary winding will be doubled; if the secondary has half as many turns as those in the primary, then the induced voltage in the secondary coil will be half as great as that in the primary winding. The first example illustrates the principle of a step-up transformer, whereas the second illustrates the principle of a step-down transformer. The power output of the transformer, however, is theoretically equal to the input (all losses due to impedance, heating effect, hysteresis, and eddy currents in the transformation being neglected).

Each transformer has a factor called the "*transformer constant*," which is the ratio of the number of turns in the primary to that of the secondary coil of the transformer. The ratio of a transformer may be expressed as 1:10, 1:20, 1:100, 1:1000, etc.

11. The Transformer Formulae.—In a foregoing section mention was made that the induced voltage in a coil depends upon the number of turns of wire in that coil. If an alternating voltage having a sine wave form is impressed across the primary winding of a transformer, and the voltages in the primary and

the secondary coils are measured by appropriate voltmeters, it will be found that to a close approximation the ratio of the primary voltage to that of the secondary is equal to the ratio of the number of turns in the primary to that in the secondary of the transformer. The relation may be expressed in an equation form (approximately) as

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \quad (12)$$

from which,

$$V_2 = \frac{N_2 \times V_1}{N_1} \quad (13)$$

in which, V_2 is the induced voltage in the secondary, V_1 is the primary voltage, and N_1 and N_2 are respectively the number of turns in the primary and in the secondary windings.

We have already seen that the respective voltages in the primary and in the secondary are respectively proportional to the number of turns in the corresponding coils of the transformer, and that the voltage in the secondary is changed in magnitude at the expense of the current value. This means that when the voltage is stepped up in the secondary, the current is reduced in a manner that the product of the secondary voltage and the current is same as the input power in the primary coil. Thus, the power input in a transformer is approximately equal to the power output. This relation may be given in an equation form as

$$V_1 I_1 = V_2 I_2 \quad (14)$$

from which we obtain,

$$V_2 = \frac{V_1 I_1}{I_2} \quad (15)$$

where, V_1 and I_1 are respectively the voltage and the current in the primary winding, and V_2 and I_2 are the respective quantities in the secondary of the transformer.

A well-designed transformer should have an efficiency of 95% to 98%, while most of the inexpensive commercial transformers achieve an efficiency of between 80% and 90%. Such an effi-

ciency is a direct function of the power factors in the respective windings of the transformer.

Example:—A power of 500 watts is impressed on the primary side of a transformer at 125 volts. If the transformer ratio is 1:80, find the voltage and the current in the secondary coil of the transformer. Also find the current in the primary.

The voltage in the secondary will be equal to $125 \times 80 = 10,000$ volts. The secondary current will be $500/10,000 = 0.05$ ampere. The current in the primary will be $500/125 = 4$ amperes.

CHAPTER III

THE X-RAY APPARATUS

1. Introduction.—Just as there are various types of x-ray apparatus adapted to varied usage in medical radiography there are also a number of classes of industrial radiographic equipment used to meet various requirements of the prospective user. Though constructed principally on the same mechanical and circuit arrangements, the operative requirements of these machines make it necessary to design them to suit the particular purpose. For instance, unlike medical equipment, which is very flexible as to the movement and angulation of the x-ray tube, the hermetic unit incorporating the x-ray tube and its cooling auxiliaries need not be flexible to effect the angulation to the material to be radiographed in routine production work. Indeed, since the majority of the industrial materials x-rayed are of routine production, the x-ray tube may be positioned at a fixed distance from the table top of the apparatus (although in some equipment the x-ray tube moves up and down covering a fixed distance), allowing only the movement of the hood protecting the operator against disseminated x-rays. This permits the adoption of exposure techniques which, when once standardized, need not be changed again unless the existing x-ray tube is replaced by one of different load capacity and roentgen output.

For special type of work, such as large steel pressure vessels, concrete pipes and ducts, bridgework frames, penstocks, aeroplane fuselage and wings, welds in railway beams, steamship structures, etc., where the part to be x-rayed cannot be conveniently brought to the x-ray laboratory for inspection, mobile radiographic units which afford extreme flexibility of use in the angulation and approximation of the x-ray tube are employed. These units are generally known as "field equipment" and may be adapted to innumerable radiographic procedures.

The load capacity of the x-ray apparatus varies with the particular purpose for which it is intended. Generally, for steel, beryllium bronze, and in general for heavy metals up to six inches thick, voltages from 200 kilovolts to 600 kilovolts at 5 to 8

milliamperes will be sufficient. Other special equipment operating on voltages from 1 million to 10 million volts at 2 to 3 milliamperes are also known to the industry. These units can penetrate steel one foot in thickness or over, as the wavelengths produced at these voltages approximate those of short-wave gamma radiations from radium. However, for aircraft industrial applications where usually light-weight materials are utilized the potential requirements do not exceed 220 kilovolts with current values varying from 3 to 35 milliamperes, being inversely dependent on the voltage used. The exposure time for routine production varies from several seconds to ten minutes. This factor also depends on the x-ray tube focal spot area, which generally ranges between 0.6 mm to 6.00 mm effective. The use of larger effective foci, however, are not uncommon in work for heavy and thick construction where a high intensity x-ray radiation becomes of significant importance. But, owing to the tendency of the image losing fine definition when tubes of large focal area are employed, the object-film distance usually is made relatively large to offset this condition.

In order to generate x-rays, it is essential to apply a high-voltage unidirectional current to the x-ray tube. Since unidirectional or direct current is not ordinarily available at voltages required to produce x-rays, rectified alternating current is generally used.

Since the voltage from the main lines led into the x-ray apparatus is of the order of 115 or 230 volts, a transformer is employed, which steps up the low voltage alternating current to a thousand fold. The high voltage current then is sent usually through a rectifier means, which converts it into a unidirectional current. An alternating current when converted into a unidirectional current is known as "*rectified current*." When a rectified current is allowed to pass from the cathode to the anode of the x-ray tube, invisible radiations previously referred to as *x-rays* are emitted from the face of the anode.

With a modern type of x-ray apparatus, the voltage and the current supplied to the x-ray tube can be accurately controlled and varied independently. The penetrating quality of the x-rays can be modified through a wide range by varying the voltage and without appreciably affecting the magnitude of the current



Courtesy Aircraft X-Ray Labs.

Plate I:—A Typical 125-Kv.P. Industrial Unit for Routine Radiographic Work.

through the tube. Conversely, the current through the x-ray tube can be varied within wide limitations without affecting the quality (penetrative power) of the x-rays. The same apparatus may be used for a variety of classes of service just by changing the accessories and the settings of the controls. The types of service usually expected from an industrial x-ray tube are special research work, radiography of concrete constructions, and metal structures and fabrications.

Industrial radiography has also occupied a prominent realm in the field of plastics, examination of fruits, and lately in art. Hard rubber moldings, bakelite frames and panels and cylinders, fiber products, coal derivatives, radio tubes, tooth-paste tubes, and woodcraft are x-ray tested for imperfect fabrications and for possible inclusion of foreign matter. In the field of art, the examination has been confined to the determination of genuinity of those paintings considered as original. All old paintings (which are done with inorganic pigments in contrast with organic dyes used in modern paintings) when retouched or tempered in any manner can be readily detected, and imitation work can be discriminated from that of true masterpiece.

Each year new developments and certain physical modifications are brought about in the construction and design of the different parts of the x-ray machine without radical departure from the principle on which the apparatus functions. Such constructional improvements, however, are believed to have been confined primarily to an increase in efficiency of the x-ray output, flexibility of use, absolute safety to the operator, and substantially longer life of the apparatus or its parts.

2. Essentials of An X-Ray Apparatus.—An x-ray generating apparatus essentially embodies a source of 50 or 60 cycle alternating current of between 30 to 60 amperes at 115 to 230 volts. Before this power is impressed on the x-ray tube, it is caused to pass through a voltage-controlling device called an "*autotransformer*," which supplies the desired voltage to the primary winding of the x-ray transformer, which, in turn, steps up this voltage. The high tension current from the secondary side of this transformer is led to a rectifier mechanism which may be of either a mechanical type or an electronic type (thermionic); and, after having been rectified the current is allowed

to pass through the x-ray tube for inciting it to emission.

Before an x-ray tube may be made to produce x-rays, it must have a supply of *cathode rays*. The latter are generated at the cathode filament of the tube. This filament is heated to a high temperature from a separate source independent of the high-tension circuit. A step-down transformer, generally known as Coolidge filament transformer, is employed for this purpose. This transformer receives a small power from a portion of the autotransformer circuit. More commonly, this power is taken directly from the 115-volt alternating current supply line, and it is then controlled by a choke coil before it is impressed on the transformer primary. An ammeter placed in series with this choke coil serves to determine the amount of current delivered to the primary winding.

The leads from the secondary winding of the Coolidge transformer, carrying between 3 to 15 amperes at 6 to 18 volts depending on the type of x-ray tube and on the x-ray output desired, are directly connected to the filament of the x-ray tube. The magnitude of this current determines the filament temperature and thereby the milliamperage across the x-ray tube. An increase or decrease of filament temperature respectively increases or decreases the milliamperage across the x-ray tube. Since the secondary side of this transformer is sustained at the same potential as the x-ray transformer, the two windings (primary and the secondary) are insulated from each other, by immersion into a refined mineral oil, to the full voltage of the x-ray transformer.

During operation of the x-ray apparatus, occasionally there occurs voltage fluctuations in the high tension circuit, which effect sometimes may materially curtail the x-ray emission. The exposed film then may not have the proper density essential for accurate diagnosis of the radiograph. This fluctuation is due to a sudden and temporary drop of voltage in the supply line especially when this is connected to a circuit using high-torque motors, welding apparatus, magnetic coils, etc. In order to obviate the annoyance by such effects, a device called a *stabilizer* is generally employed. This device is placed in the high tension circuit between the rectifier system and the x-ray tube, and it suppresses any possible fluctuations of the current to the x-ray

tube. A milliammeter, sometimes incorporated together with the stabilizer, is placed in series with the anode of the x-ray tube, and determines the current passing through the tube during exposures.

In series with the primary side of the x-ray transformer is an automatic *timer* which controls the exposure of the film to be x-rayed. A *potential indicating meter*, connected across the auto-transformer, indicates the potential applied to the primary of the x-ray transformer in arbitrary units. A complete scale of these arbitrary units is made into a chart form calibrated to give the actual voltage applied to the tube. By reading the potential meter and referring to the calibration chart for the corresponding voltage, the impressed tube potential may readily be determined. In most x-ray machines of recent manufacture, the potential indicating meter is replaced by a *kilovoltmeter* which registers the actual tube voltage directly.

In the case of a mechanically rectified apparatus, a *synchronous motor*, and a *polarity indicator* are included. The purpose of the latter is to ascertain, previous to the contacting of the x-ray switch, that the correct polarity of the current through the x-ray tube will be effected when the latter is energized; that is, to make sure that the tube current will have a direction from the cathode to the anode.

3. The X-Ray Controls and Indicating Instruments.—A diagram representing the control panel of a typical x-ray ap-

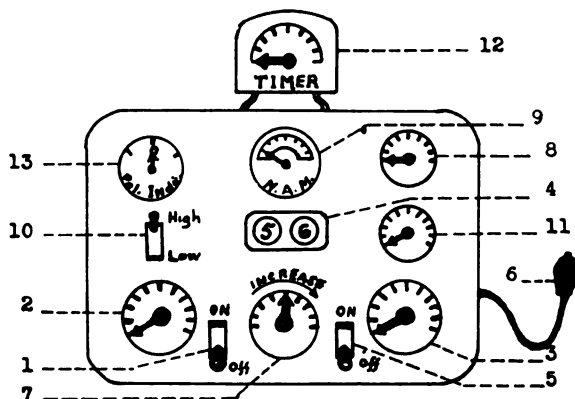


Fig. 14a, Diagram of an X-Ray Control Panel.

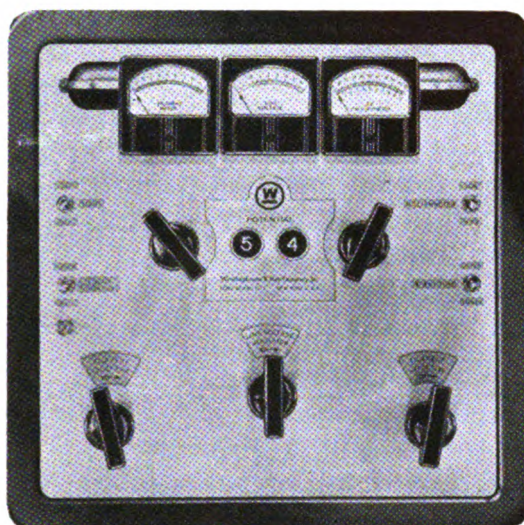


Fig. 14b. Commercial Form of the X-Ray Panel.

paratus is given in Fig. 14a, in which the main switch (1) controls the primary circuit, and when it is in the "ON" position the autotransformer and the filament transformer are energized, and the x-ray tube is lighted. If the machine has valve tube rectification system, the filaments of the valve tubes (rectifiers) are also lighted in this operation.

Now the coarse adjustment of the autotransformer control (2) may be varied in steps of 10 kilovolts and the fine adjustment control (3) in steps of 1 kilovolt over a range of 10 steps until the desired kilovoltage is obtained, as registered by the numerals at the dial (4). This dial indicates the true useful kilovoltage to be impressed on the x-ray tube when the primary x-ray switch (5) is turned to "ON" position.

When the part to be radiographed is properly aligned with the x-ray tube, and adequate identification numbers are placed on the film, the auxiliary push-button switch (6) is contacted for exposure. It should be kept well in mind that under no circumstances should the autotransformer controls be adjusted while the x-ray tube is in operation.

Number (7) is a stepless induction type x-ray tube filament control, which offers a smooth regulation of the filament tempera-

ture over the entire milliamperage range. To increase the filament current, the control knob must be rotated in the direction of the arrow, and to decrease this current the operation is enacted in the reverse direction. This control may be adjusted even when the x-ray tube is in operation, but care should be taken that the knob is rotated slowly so that the milliamperage across the tube will not exceed the rated capacity of the tube. The ammeter (8) will indicate the amount of amperage delivered to the tube filament. Indirectly, this meter indicates the exact milliamperage that will pass through the x-ray tube when energized.

In the high tension circuit on the same side as the x-ray tube anode is placed a milliammeter (9), which indicates the number of milliamperes passing through the tube during exposures. The instrument may be built together with a current stabilizer in one unit, which, when set to the required milliamperage by actuating a knob on the face of the instrument, will deliver the exact amount of milliamperage to the x-ray tube.

The scale of the milliammeter varies in calibration from 0-60 to 0-1000 milliamperes for radiography, depending on the type and make of the x-ray apparatus, and from 0 to 15 milliamperes for fluoroscopy. The shunt switch (10) effects the change from one scale reading to the other. In some makes of machines this shift from one to the other scale reading correspondingly changes the area of the cathode ray impact on the surface of the x-ray tube target.

Connected in series with the secondary side of the autotransformer is a resistance control (11), which is used only for fluoroscopic work, and it is cut out of the circuit during radiography. Because of the high efficiency of the autotransformer as regards its power conservation, the use of a rheostat is gradually becoming obviated. A rheostat regulates the power in a circuit at the expense of the dissipation of current in the form of heat, while an autotransformer effects this adjustment by producing a counter-electromotive force in its secondary coil, which regulates the power in relation to the settings made on the transformer controls.

From the x-ray timer (12) any desired exposure time may be obtained within its range. Three general types of this device

are now in common use. The synchronous timer, which serves as an accurate timing switch, is actuated by an electric synchronous clock mechanism. It has two ranges from 0 to 3 seconds in steps of $1/20$ th second, and from 0 to 30 seconds in steps of $1/2$ second. The second type is an impulse timer. An elegant timer of this order is the KX-7 unit offered by the General Electric X-Ray Corporation. With this timer, an exposure as short as $1/120$ th of a second corresponding to one impulse ($1/2$ cycle) of a 60-cycle alternating current wave can be made. The use of this timer, however, is principally confined to medical radiography, and it finds little or no use in industrial work. A third type is an electric clock mechanism with which exposures up to one-half hour may be made. The device has found considerable use in the field of industrial radiography, owing to the long exposure time employed especially in radiographing heavy metals.

Occasionally it becomes desirable to test the accuracy of the synchronous timer. A device known as the spinning top may be employed. But, a simpler method is to drill a one-millimeter hole through a sheet of lead ($8'' \times 10''$), and to radiograph the film while pulling the lead at a uniform speed over the exposure area of the film.

The frequency of the x-ray impulses is dependent upon the cycle of the current energizing the x-ray tube. For instance, for a 60-cycle full wave anode voltage, the number of pulsations per second will be 120, while for a half-wave current it will be 60. Therefore, an exposure of, for instance, $1/10$ th second will consist of 12 dots on full-wave rectification, and 6 dots on half-wave rectification. It will be evident then that any variation in the number of dots recorded other than that calculated for a given exposure time will indicate a condition of inaccuracy in the timer mechanism.

A polarity indicator (13) is necessarily installed on a mechanically rectified x-ray machine in order to ascertain in what direction the current through the x-ray tube will tend to flow when the x-ray switch is closed. The rectification in this type of machine being effected by the rotation of the synchronous motor in step with the alternations of the current through the rectifier switch, a commutator built on the shaft of this motor permits

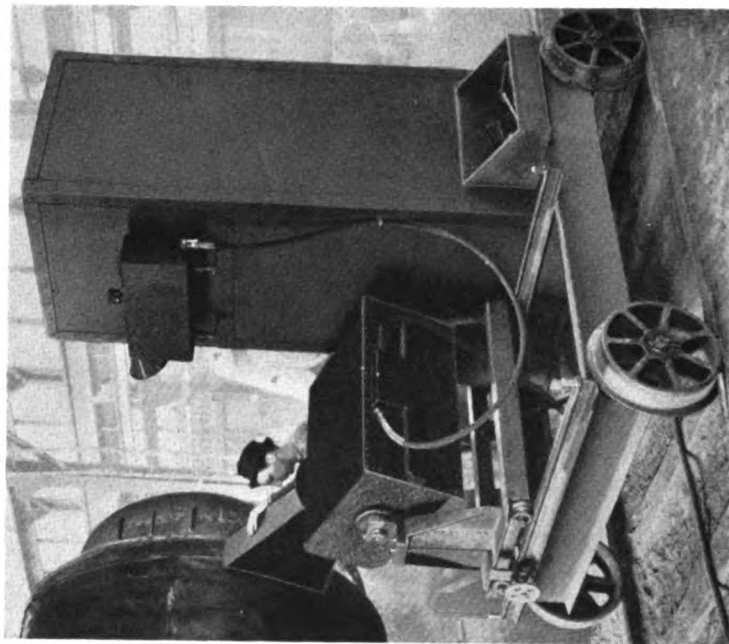


Plate III:—General Electric 300-KV Mobile Industrial Unit.

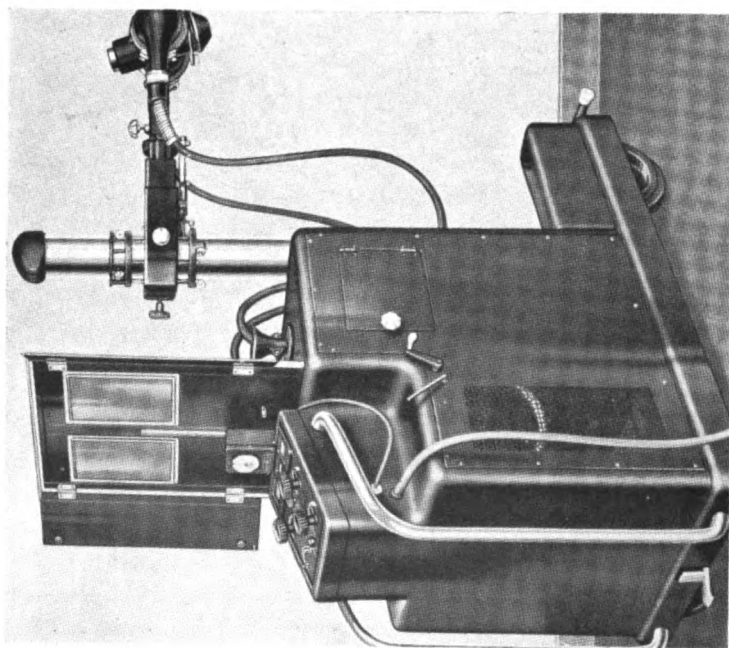


Plate II:—Keleket 150-KV Mobile Industrial Unit.

only one-half cycle of the current to pass through the polarity indicator, which registers either "correct" or "incorrect" according to the polarity of the half-cycle, or, the alternation caught by the commutator.

When the indicator registers "correct," the direction of the current through the x-ray tube will be, when the x-ray switch is closed, from the cathode to the anode. If the indicator registers "incorrect," a reverse current will tend to pass across the x-ray tube when it is energized, and no x-rays can possibly be produced. Therefore, the main switch is turned off, and turned on again a number of times until the indicator registers "correct."

A polarity indicator is not necessary in the case of a machine operating on self-rectification or with valve tube rectification system, since the direction of current flow through the x-ray tube will always be from the hot cathode to the anode, by virtue of the circuit arrangement in these types of rectifications.

4. Manipulation of the X-ray Apparatus.—To operate the x-ray apparatus, the main switch (1) of Fig. 14a is first turned on, which lights the filament of the x-ray tube, and readings will register on the filament ammeter and on the potential indicator (if there is any) of the line voltage. With a given radiographic technique, the voltage is regulated by advancing the autotransformer controls (2) and (3), and the shunt switch (10) is set to the proper value in accordance with the amount of milliamperage to be passed through the x-ray tube; e.g., if a current of less than 15 M.A. (milliamperes) is to be used in the technique the switch is set on the reading on the face of the panel marked by "small" or "low," and for high current values this button should be set on "large" or "high." Now, the filament control (7) is rotated until the desired milliampere setting is obtained on the ammeter (8); and, finally the x-ray timer (12) is set for the required exposure time.

Next, the part to be radiographed is properly positioned with the film placed underneath the part and perpendicularly to the x-ray beam. The x-ray tube is correctly distanced, and aligned so that the hypothetical beam issuing from the center of the target at right angles to the tube axis falls perpendicularly to the center of the exposure area of the part and that of the film. This hypothetical beam is known as the "*principal ray*" or "*central ray*."

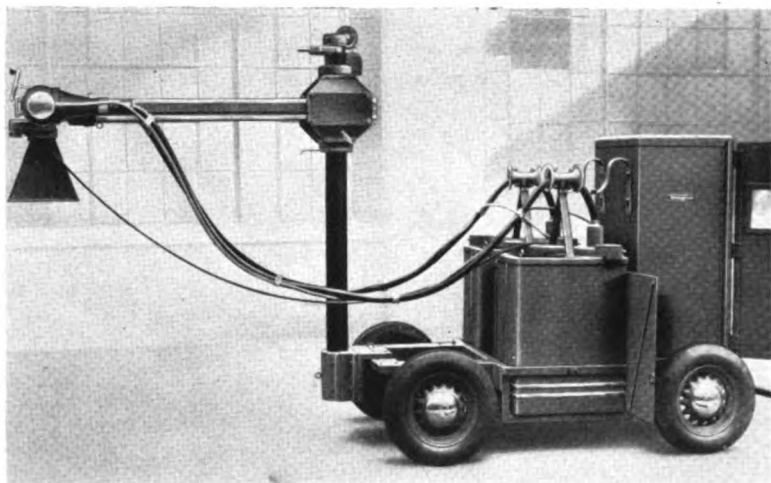


Plate VI:—Westinghouse 220-KV Industrial Mobile X-Ray Unit.



Plate VII:—230-KV X-Ray Unit Which Can Radiograph Steel Up to 3 Inches Thick, 2.5 Feet Wide, and 20 Feet Long.

Courtesy Aircraft X-Ray Labs.

All settings are checked carefully before energizing the x-ray tube. Having placed proper identification numbers on the film, the x-ray switch (5) is turned to the "ON" position, and the auxiliary push-button is pressed and held in that position until the timer automatically opens the circuit when the set exposure time is elapsed. If desired, similar exposures with the same technique may be made on other films by simply pressing the x-ray button for the exposure. Exposure settings for other techniques may be had by re-adjusting the different controls, as outlined above.

When the exposure is made, the main switch is turned off. If routine production work is being conducted, the latter switch is not turned off until all radiographic work is completed on that given lot. The exposed films are wheeled to the processing room where they are developed, fixed, washed, and dried. The radiographs then, are transferred to the diagnostic department for final examination and report.

5. Fluoroscopic Procedure.—Generally industrial inspection of metals does not necessitate fluoroscopy except in exceptional cases. Plastics, molded products, fruits, wooden fabrications, pastes in tubes, electric light globes, radio tubes, etc., however, may be advantageously fluoroscoped, which procedure will save considerable time and expense since no films will be needed.

When a beam of x-rays is incident on certain chemical substances, such as Calcium Phosphate, Barium Platinocyanide, Anthracene, Calcium Tungstate, or Zinc Sulphide, they become fluorescent with a characteristic glow varying from blue to applegreen, depending on the chemical used. The intensity of the fluorescence varies with the amount of radiation received by the chemical. The effect is due to the absorption of the energy of the short-wave x-rays by the fluorescent chemical and its subsequent transformation into characteristic visible radiation.

If any one of these fluorescent substances, for instance, Calcium Tungstate, is ground into a fine powder and mixed with a binder, and the resulting mixture is applied uniformly on a cardboard support and mounted in a frame covered with lead glass, the assembly offers an elegant means of recording the different densities or thicknesses of parts or castings traversed by x-rays. Such an apparatus is called a *fluoroscopic screen*.

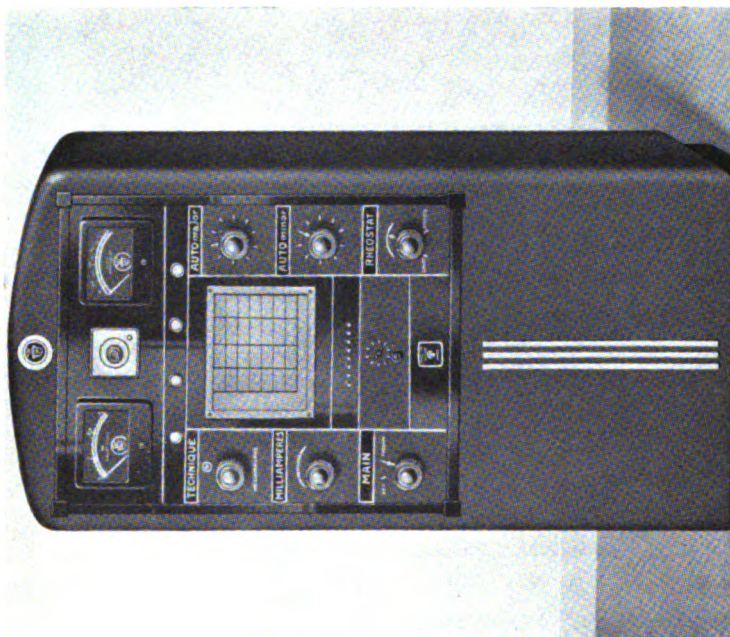


Plate V:—Keleket Control Panel for 400-KV Unit.

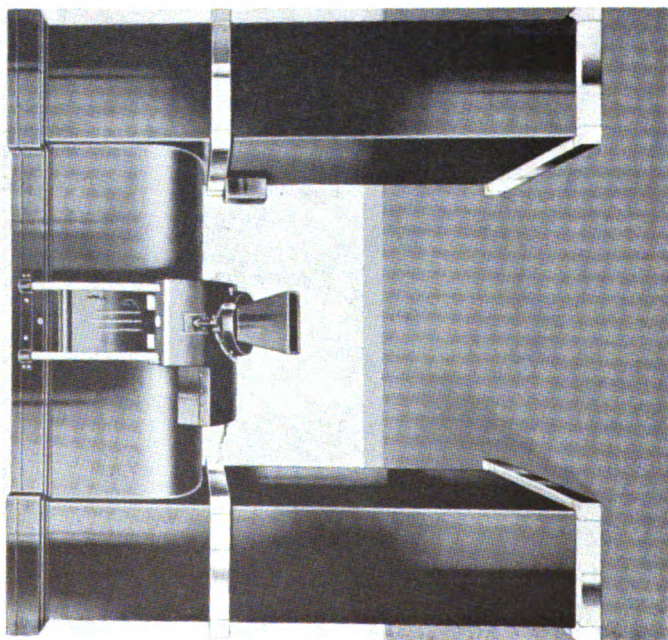


Plate IV:—Keleket 400-KV Industrial Unit.

An x-ray machine used for fluoroscopic work has its x-ray tube usually placed underneath a table with the fluoroscopic screen mounted on the table top. A mirror of the same size as the screen is mounted at 45° angle which subtends the two surfaces. The screen and the mirror assembly is covered by a cubicle lined with sheet lead to protect the operator, who sits next to the machine and looks into the mirror to diagnose the part under consideration. The part is generally placed between the x-ray tube and the fluoroscopic screen.

In diagnosing industrial materials with the aid of a fluoroscope, the x-ray push-button switch is replaced by a foot switch, which provides a convenient way of switching the x-ray circuit on and off, enabling the operator to use his hands in adjusting the part to the desired position. In some fluoroscopic machines, the parts to be fluoroscoped are placed on a moving conveyor, and the operator sorts these parts as they pass along.

6. Rectification, and X-Ray Circuits.—The conversion of an alternating current to one of unidirectional current is fundamentally known as *rectification*. Since an unidirectional flow of current is essential in the energizing of the x-ray tube, the high tension current entering the x-ray tube must necessarily be made to flow from the cathode to the anode to produce an emission of x-radiation.

The rectification may be accomplished by one of the following methods now generally employed: (1) By the x-ray tube itself (self-rectification); (2) By a synchronous mechanical rectifying unit; (3) By cuprous oxide rectifying discs or plates; and, (4) By one or more thermionic tubes, or, gas-filled rectifier valves.

(A) **SELF-RECTIFICATION (Half Wave)**:—The simplest type of rectification is accomplished by the x-ray tube itself. In a modern x-ray tube, the cathode filament is heated to incandescence so that it will emit electrons, while the anode is kept at a comparatively low temperature. If now a sufficiently high potential from an alternating current source is sustained between the cathode and the anode, the electrons which are emitted from the filament will be drawn to the anode during every other alternation of the current when the anode is at a positive potential. This permits the current to flow across the tube only during that half-cycle whose direction is from the cathode to the anode. That is, the electrons



Plate VIII:—Industrial X-Ray Units for Routine Radiographic Production Can Radiograph
Between 3000 to 5000 Parts Daily.
Courtesy Aircraft X-Ray Labs.

are discharged to the anode during every alternation when the cathode filament is negative. The other half-cycle is suppressed by the anode when it is negative, since its temperature is below that required for the emission of electrons.

The quantity of electron emission from the cathode determines the magnitude of the current which will flow across the tube, and the emission is directly dependent on the temperature of the cathode filament. That is, the higher the temperature of the filament the greater the amount of electron emission and hence a greater current will flow across the x-ray tube.

The amount of current load that an x-ray tube can withstand is limited. Therefore, it should not be used continuously for periods longer than its rated capacity. If this rating is exceeded, there is a tendency for the temperature of the target focal area to rise to incandescence by the continuous impact of the concentrated beam of electrons from the cathode (cathode rays). This tends to set up an inverse current across the x-ray tube, in which case the life of the tube is shortened, or, it may be cut short.

An x-ray tube functioning as its own rectifier should be furnished with a cooling system at its anode end in order to conduct the heat that is produced by the continuous impact of the cathode ray (electrons from the cathode). The cooling may be accomplished by employing an anode material of high heat conductivity together with the inclusion of a radiator. The prevalent method of cooling the x-ray tube is by immersing it in a highly rectified mineral oil which circulates, by means of an electric pump, through heat radiators on which air is blown from an electric fan.

Owing to the fact that the x-ray tube can function as a self-contained rectifier as well as an x-ray generator in conjunction with a step-up transformer, the assembly permits the construction of a very simple and compact portable unit, which may be energized from the nearest electric service outlet of an ordinary 115 to 230-volt circuit.

Fig. 15 represents the diagram of a simple circuit in which an x-ray tube functions as its own rectifier. When the secondary of the filament transformer *F.T.* furnishes a small current at a low potential to the filament of the x-ray tube *T* and

a high potential from the secondary of the x-ray transformer *X.T.* is sustained between the electrodes, the tube will be incited to x-ray emission.

But such a circuit will prove impracticable for different techniques requiring various tube currents and kilovoltages. Therefore, a more feasible circuit which includes means for controlling the milliamperage and the impressed kilovoltage is one that contains an autotransformer in its primary circuit to regulate the voltage to the x-ray transformer. This also contains a filament-heating transformer to control the tube milliamperage, and electric measuring instruments connected in their respective circuits.

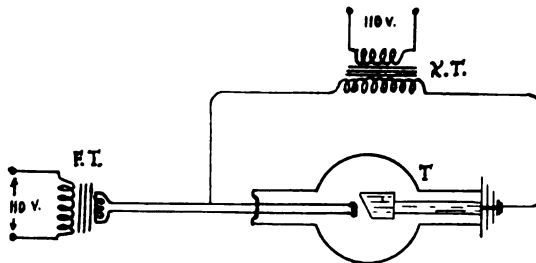


Fig. 15. A Simple X-Ray Generator Circuit.

A diagram of an x-ray circuit in which means are included for controlling the current and the potential of the x-ray tube for different exposure techniques is given in Fig. 16a, and the wave forms of the current and the potential are represented graphically in (b).

Referring now to the circuit, (1) represents a fuse having a current carrying capacity from 30 to 60 amperes at respectively 115 to 230 volts, and is placed between the supply line and the x-ray circuit to protect the various mechanisms of the machine from becoming damaged when the circuit is overloaded. When the main switch (2) is closed, it allows the current to flow to the autotransformer (3) and to the filament transformer (15), which is a step-down type. In series with the autotransformer is a rheostat (4) (optional) and in parallel with it is a potential indicating meter (5), which indicates the voltage to the primary side (8) of the x-ray transformer. The potential meter (5), however, may be calibrated to register the kilovoltage of the x-ray tube directly.

In the circuit furnishing current to the primary of the x-ray transformer is placed an exposure timer (6), and in series with it is the x-ray switch (7), which may be replaced by an adjustable automatic circuit-breaker. In the latter case a push-button mechanism incorporated in the exposure timer may be substituted for the x-ray switch.

One of the leads from the secondary (9) of the x-ray transformer is connected to the cathode of the x-ray tube (12), and the other lead is carried through a milliammeter (11) to the anode of the tube. The secondary (9) is further connected at its center with the ground as at (10).

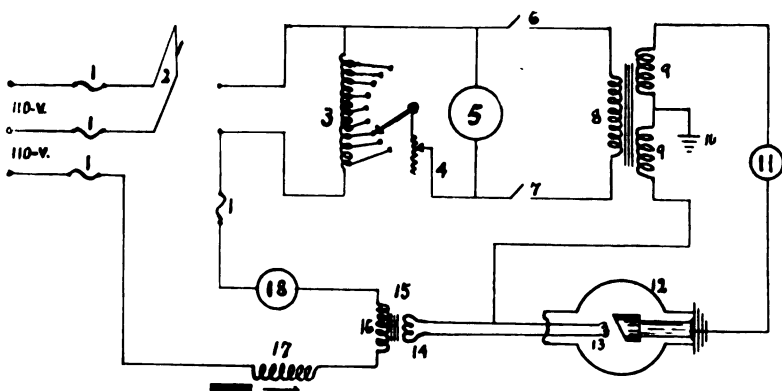


Fig. 16a. The Circuit Diagram of a Self-rectified X-Ray Apparatus.

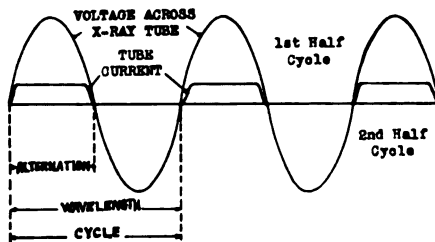


Fig. 16b. The Current and the Voltage Wave Forms.

The x-ray tube filament (13) is heated by a small current furnished from the secondary (14) of the Coolidge transformer (15). This current is indirectly controlled by a choke coil (17), and its magnitude is determined by the ammeter (18) placed in series with the primary (16) of the transformer.

In most x-ray machines, the milliammeter indicating the current passing through the x-ray tube makes a series connection

at the center of the x-ray transformer secondary which is center grounded. The potential meter (5) in some of the valve tube rectified machines is replaced by a voltmeter calibrated to read the high tension potential in kilovolts directly.

It must be clearly understood that self-rectification is only feasible when a diagnostic type of x-ray tube furnished with coolers is employed in the apparatus. As for air-cooled universal tubes, in which the target becomes heated to the temperature of electron emission and hence the current through the tube can pass in both directions, self-rectification becomes an utter failure, as this may damage the filament or cause the puncture of the tube. A universal x-ray tube, therefore, should never be put into use if it is expected to rectify its own current. Accordingly, a full-wave rectified current is the most desirable with this type of tube.

(B) MECHANICAL FULL-WAVE RECTIFICATION.—Up to recent years mechanical rectifiers have had extensive application due to their robust construction, low cost of maintenance, and their applicability to various industrial requirements. The invention of the device is attributed to C. S. Snook, who first developed, in 1908, the transformer pole-changing device quite akin to present *cross-arm* or *disc* type rectifier, which is essentially a *rotary switch* whose speed of rotation is synchronized with the frequency of the alternating current exciting the x-ray tube. That is, the cross-arm, also known as the rotary switch, is rotated by a synchronous motor at a speed equal to half the supply frequency in cycles per second. For a 60-cycle current, then, the rectifier switch rotates 30 times per second, and for 50-cycle current, it rotates 25 times per second.

The purpose of the rotating switch is to rectify the high tension alternating current before it is delivered to the x-ray tube. This is accomplished by arranging two pairs of contactor arms coupled to the shaft of the synchronous motor, which is insulated from the contactors, in such a manner that the mid-point of each arm is positioned at 90 degrees from the corresponding point of the successive arm. Each pair, functioning simultaneously, closes the circuit during each alternation of the current in the secondary of the transformer by contacting the corresponding stationary brushes attached to the aerial circuit.

The interval of time elapsing during the contact between the

cross-arms and the collectors determines the portion of each alternation used. This value is also dependent upon the peripheral length of each arm in respect to the collector brush. With earlier machines, this interval has been very short, and consequently only a small upper portion of the wave peak is utilized to produce x-rays. This is, however, of advantage to some extent in that the x-rays thus produced are more penetrating, whereas were the lower portions of the wave also utilized the condition would unavoidably contribute to the unnecessary heating of the anode without improving the quality of the x-ray emission.

To rectify the alternating current, the rotary switch (either four-arm or disc type) is rotated by a synchronous motor, which is operated on the same current supply as the x-ray tube. Since the shaft of this motor is continuous with the axle of the rectifier disc, or the cross-arm, each time the armature makes a complete rotation the cross-arm also makes a complete rotation.

During each revolution of the rectifying element, the current through the system alternates four times, each alternation passing consecutively through each pair of the cross-arms. As the current changes polarity, or proceeds one alternation, simultaneously each pair of the cross-arms rotates 90 degrees, and becomes coincident with the next set of collector brushes from the x-ray aerial. This changes the circuit connection of the tube, and at the same time, reverses the direction of the flow of current during this alternation and causes it to run in the same direction as the preceding alternation through the x-ray tube. Consequently, the process permits both halves of the cycle to flow in the same direction, thus rectifying the current that excites the x-ray tube.

At present, the use of a mechanically rectified unit is confined to medical work, although its use in industrial field is not uncommon. Most of these units have been installed before the valve tube rectification gained prominence in recent years. The mechanical rectifier has, however, its advantages over the valve (tube rectifier) rectification in that the former does not have parts that get out of order, or otherwise fail to function unexpectedly, as might be the case with a valve tube whose filament has a tendency to burn out any time while the tube is in use.

Furthermore, the mechanical rectifier produces more of the penetrating x-rays, since only the peaks of the current waves are utilized. This eliminates the use of filters for certain radiographic techniques, since the x-rays issuing from the x-ray tube utilizing the voltage peaks are of rather homogeneous wavelengths compared to those given off from a valve-tube rectified apparatus. On the other hand, valve tube rectification has many distinct advantages over mechanical rectification, and we shall further take this up in detail in our discussion on valve-rectification system.

The circuit diagram of a mechanically-rectified apparatus is given in Fig. 17a, and the curve of the useful portion of the pulsating voltage across the x-ray tube is shown in (b).

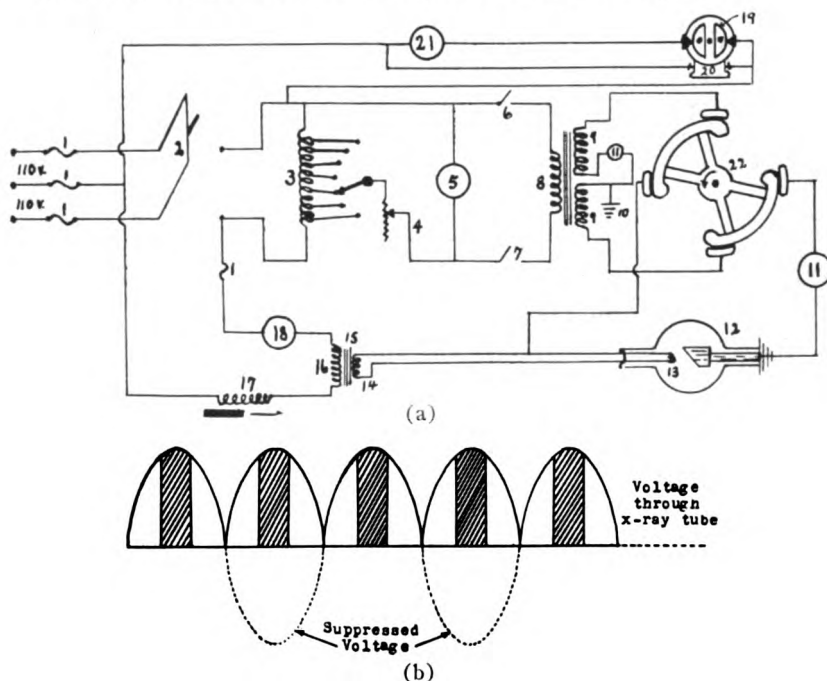


Fig. 17. Four-Arm Full-Wave Rectification. (a) The Circuit Diagram, and (b) The Voltage Wave Form.

In the figure, a polarity commutator (19) is attached at one end of the shaft of the synchronous motor (20), and furnishes the current that actuates the polarity indicator (21). Number

(22) designates one pair of the cross-arms and its circuit arrangement. For convenience of illustration the second pair of the arms is eliminated from the diagram.

The commutator consists of a disc formed by two bronze plates having half-moon shapes and insulated one from the other by mica or air-gap of about 1-mm thickness. The purpose of having the two separate discs co-axially mounted together is to suppress, by this arrangement, each half of the alternating current cycle and to allow a unidirectional current through the polarity indicator (21), which, as was explained previously, indicates the would-be direction of the current through the x-ray tube when the latter is energized.

(1) *The Autotransformer*.—Built on the same principle as a potentiometer, an autotransformer offers an ideal means of control over the high tension voltage of the x-ray circuit. The device consists of a single winding around a soft iron core. This winding takes the place of both the primary and the secondary of an ordinary transformer.

If the two extreme ends of the autotransformer coil are connected to the supply line, then this portion will represent the primary winding. An electrical connection made from one of these two leads at either extreme end to a tapping taken from any given point on the coil will constitute the secondary winding. Therefore, taking suitable tappings from the different sections at intervals of definite number of turns of wire on the transformer winding affords the transformer to vary its output with a relatively comprehensive selection of voltages with each shift from one tapping to the other. These tappings may terminate at suitable metallic buttons over which the transformer control knob conveniently slides during a shift from one voltage to the other.

The device shown in Fig. 18 has two sets of dial studs, and its winding consists of the two corresponding sections, one of which, marked by *F*, has smaller number of turns and contains practically as many tapped-in portions as the other section *C*. The division of the winding into two sets of tappings affords the advantage of two different selections of voltages. The selection from one dial, *C*, varies the potential, for instance, in steps of 10 volts, and a finer control of voltage, for instance, in 1-volt steps is secured from the other dial stud in *F*. An ar-

range such as this offers a uniform potential control from 10 volts to 225 volts, the supply voltage, in steps of one volt. Since such a fine voltage selection will necessitate the building of a bulky unit, most x-ray machines are equipped with two sets of voltage control dials, in which the voltage is varied in steps of 2 or 3 volts, thus affording a more compact construction of the autotransformer.

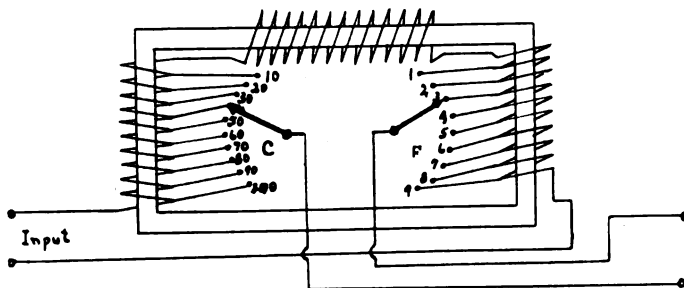


Fig. 18. The Autotransformer.

The input energy in each set of winding of the autotransformer is uniformly distributed throughout its entire range. Hence, the voltages between any two consecutive taps of a given set on the winding are equal, since any two of the inter-tap spaces contain the same number of turns. For instance, in section *F*, the voltage between the buttons 6 and 7 is the same as that, say, between the buttons 2 and 3. Similarly, any two sections in *C* have equal potential differences. By adjusting these controls to suitable buttons, a uniform selection of voltages up to the supply voltage can be conveniently obtained.

The principal objection to this arrangement is that the autotransformer control cannot be varied while the x-ray tube is excited, since in shifting the control from one button to the other the x-ray circuit will be opened, subjecting the x-ray tube current to sudden fluctuations which will increase the burden on the tube. This difficulty, however, can be overcome to some extent by inserting unipolar resistances between the studs from each tap, or by furnishing the contacting brush of the control knob with split legs, held together by a spring, so that when one leg is about to make a contact with the next stud, the other leg just releases itself from the preceding stud by the action of

the spring. Recent reports indicate that a stepless voltage controller, commercially known as "Variac" permits the continuous variation of the voltage during loading of the x-ray tube.

Unlike the potentiometer arrangement of a rheostat, the autotransformer controls the voltage output by producing in its winding a counter-electromotive force which offers an inductive resistance to the variations of voltage in its secondary to values other than set forth on the control dial. Due to this effect of self-induction, practically no power is dissipated in the form of heat (I^2R) as would be the case if a rheostat is used to accomplish this purpose. Thus, the autotransformer offers a distinct advantage over the rheostatically-controlled circuits which involve the loss of power with a consequent evolution of heat undesirable in x-ray circuits.

(C) TUBE RECTIFICATION.—The earliest type of tube rectifier comprised a glass vessel enclosing a cold cathode in the form of a small disk, and a spiral anode. The tube operated with a small amount of residual gas, which, when ionized, conducted the current across the tube when a potential was applied. But, the gas diminished by use, and therefore, it was replenished by applying a high potential to its softening device consisting of two electrodes and a mica or carbon regenerator provided in an auxiliary side tube.

The rectifying action of this tube was obtained owing to the large surface area of the cathode, which permitted the passage of the current more readily to the spiral anode when the latter had a positive polarity. The anode, however, passed a small amount of current in the reverse direction (toward the cathode) during the interval of the cycle when the cathode was positive. Obviously, then, such a tube did not provide a satisfactory means of suppressing the inverse current flow. Thus, with the advent of high vacuum hot-cathode tube, the gas-filled valve rectifier proved to be an inefficient component of the x-ray apparatus, and it soon was dispensed with.

Practically all of the present-day x-ray machines using tube rectifiers embody the *principle of hot-cathode emission*, also known as *thermionic emission principle*. That is, the cathode filament of the tube is heated to incandescence, which process permits the free electrons in the filament to acquire such high

velocities that they actually leave the surface of the metal. When a potential is applied to the electrode, the electrons (cathode rays) drift across the tube in the direction of the impressed potential gradient. As mentioned before, the number of electrons emitted is a direct function of the temperature of the filament.

At present the thermionic rectifying valve receives a marked preference in view of its presenting physical and electrical qualifications unsurpassed by any other type of rectifying unit. For instance, the thermionic valve embodies noiseless operation, reliable performance, and owing to the absence of moving or rotating parts, mechanical vibrations are completely eliminated from the apparatus. Because of the complete suppression of high voltage surges, and because of the perfect insulation of the cables (taking the place of overhead aerials) there is no spark or corona generated, and consequently, possible production of radio interferences, nitrous oxide, or ozone, is eliminated. Furthermore, since there is practically no limit to the milliamperage that can be drawn across the tube, x-ray output of any quantity limited only by the load capacity of the x-ray tube can be realized by the use of the thermionic valve. All modern industrial x-ray apparatus having separate rectifying systems are provided with valve-tubes as standard equipment.

The *thermionic valve* (rectifier) comprises a highly evacuated envelope containing a filament cathode and an electron-receiving concave anode. The latter also may be in the form of a cylinder, which, as illustrated in Fig. 20, completely encloses the cathode structure. When the filament is heated (to about $1000^{\circ}\text{C}.$) it emits electrons, the emission being in proportion to the filament temperature. The higher the temperature, the more electrons are emitted. The application of a potential difference between the two electrodes causes the electrons from the cathode to move to the anode. The velocity with which these electrons travel is dependent on the applied potential.

When the filament is heated to incandescence and a high potential alternating current is sustained across the tube, the electrons will escape during that alternation of the current when the filament polarity is negative with respect to the anode. As the filament becomes positive during the time interval of the next alterna-

tion, no electrons are emitted, and consequently the current ceases to flow across the tube—hence the function of the tube as a valve. Since the anode temperature is retained below that required for the emission of electrons, the electron flow cannot reverse its direction. Thus, the device will permit the passage of the electrons only from the cathode to the anode once every other cycle. The current, then known as “*rectified current*,” will have a half-cycle, unipolar, and unidirectional wave form.

A relation expressing the number of escaping electrons per square centimeter of surface area of the heated filament is given by Dushman's equation as

$$I = A_0 T^2 \epsilon^{-\frac{b_0}{T}} \quad (46)$$

in which, I is the maximum current in amperes at the given absolute temperature T , A_0 is a universal constant equal to 60.3 for all pure metals, ϵ is the base of natural logarithms, and b_0 is a constant equal to $\phi e/K$.

In the expression $\phi e/K$, ϕ is the work function (in volts) of the metal, e the charge of the electron equal to 4.80×10^{-10} e.s.u., and K is Boltzmann's constant having the value R/N or 1.37×10^{-16} ergs per degree, where R represents 8.314×10^7 ergs per mole per degree, and N is Avogadro's number, 6.064×10^{23} .

In Table II, are given the values of b_0 and the thermionic work functions for different metals.

TABLE II:—QUANTITATIVE VALUES OF b_0 , AND THE THERMIONIC WORK FUNCTIONS FOR VARIOUS METALS

<i>Metal</i>	$b_0 = \frac{\phi e}{K}$	<i>Work Function</i> (volts)
Calcium	35,000	2.42
Cesium	21,000	1.81
Molybdenum	51,500	4.44
Nickel	32,100	2.77
Platinum	72,500	6.27
Tantalum	47,200	4.07
Thorium	38,900	3.35
Tungsten	52,400	4.52
Zirconium	47,900	4.13

In constructing a thermionic valve-tube the same care as for an x-ray tube is exercised, since the former is subject to the same difficulties as are prevalent during the building and processing of an x-ray tube, viz., the problem of attaining the highest vacuum possible and sustaining it during the entire life of the tube; the adequate cooling of the anode which is heated by the impact of the cathode rays; the provision of a sufficiently heavy filament for supplying an atmosphere of electrons which is many times denser than that supplied by the x-ray tube filament, for a given exposure technique; and, finally, to operate the rectifier filament, as much as is practicable, below the saturation point of the tube current for all exposure techniques so as to prevent the incitation of the valve to x-ray emission.

A valve-tube operated beyond its saturation point is subject to a rise in its anode temperature as a result of a high voltage drop across it, and x-rays are inevitably produced by the valve. The condition is indicative of a dissipation of excessive power in the tube. Unless the cause is remedied the life of the tube will be impaired.

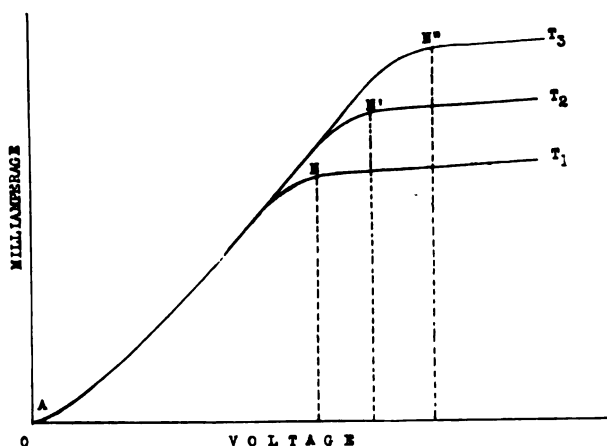


Fig. 19. Thermionic Characteristics of a Vacuum Tube.

The practical significance of the saturation current may be better understood by a reference to the illustration given in Fig. 19. As mentioned above, the primary function of a rectifier is not solely to change an alternating current into one of unidirectional phase but also to allow, because of its design of construction, an

unlimited amount of current to the x-ray tube without itself becoming incited to x-radiation. Thus, the graph in Fig. 19 is drawn by plotting the anode potentials in volts (or kilovolts, as in x-ray work) against the resultant milliamperage, the filament temperature having been maintained at a constant value T_1 , T_2 , or T_3 , as the case may be.

Referring again to Fig. 19, there are three curves plotted, the slopes of which are partially superimposed on each other, indicating that the emission of electrons under a given potential difference remains practically the same for all three values of the temperature. The curve represented by ANT_1 for the absolute temperature T_1 has a portion AN for which a change in the applied voltage produces the corresponding change in the milliamperage across the tube. But, beyond the point N no appreciable increase in the tube milliamperage occurs. Hence, the point N is known as the *saturation point* of the current for that particular temperature T_1 . A thermionic rectifier, then, should be operated within the values covered by AN , as when the voltage value is exceeded that corresponding to point N the tube will emit x-rays, and excessive heating will result, which condition may even cause the destruction of the rectifier.

The curves $AN'T_2$ and $AN''T_3$ are similarly plotted for temperature T_2 and T_3 respectively. It will be noted that as the temperature of the filament is elevated, the tube milliamperage is correspondingly increased and the saturation is reached at a higher

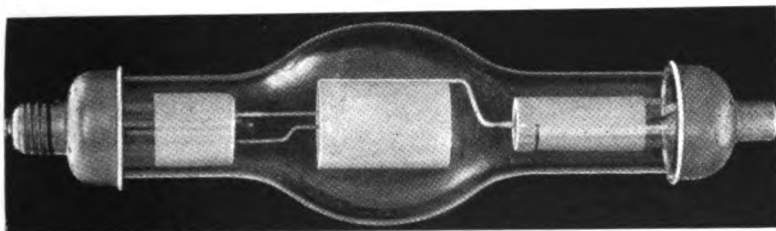


Fig. 20. The G. E. KR-4 Kenotron for 140 Kv. P.

value of the applied tube voltage. It should now be clearly understood that *any variation in voltage energy beyond the saturation point of a given tube current will affect only the speed of the electrons arriving at the anode.* Hence, a rectifier is designed to

operate below the saturation point, whereas an x-ray tube is always operated beyond the saturation point of the current.

In order to avoid an excessive power dissipation due to the operation of the rectifier at or beyond the saturation of the current, it is desirable that the rectifier filament has a larger dimension and operates at a higher temperature respective to the x-ray tube filament and temperature. An equation expressing the relation of the applied voltage to the saturation current is given as follows:

$$V = AI^{\frac{2}{3}} \left(1 + \frac{BI}{I_s - I} \right) \quad (47)$$

in which, V is the impressed potential in volts, I is the energizing current, I_s the saturation current through the tube, and A and B are constants characteristic of the given valve tube and the filament temperature.

Several types of valve-tubes are commercially available at present. Of these, the most common is known as the *Kenotron*, Fig. 20. The *Model KR-4* shown in the figure comprises a cathode having a spiral tungsten filament fixed coaxially with the cylindrical anode of sheet molybdenum surrounding the filament. This type of construction is adopted because the arrangement has proved, in practice, that the voltage drop is relatively small compared with an "end-on" type of construction. To keep the voltage drop in an x-ray tube at a minimum is important, as the r-output (x-ray emission) has direct relation to this drop.

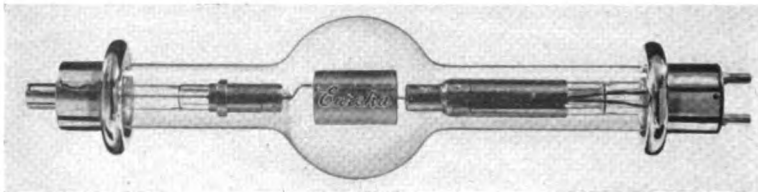


Fig. 21. The Eureka EV-10-140 Valve Rectifier.

The rectifier shown in Fig. 20 is designed for oil-immersed operation. It is rated to operate, in a four-valve rectifier unit, at a maximum permissible load of 140 Kv.P. (kilovolts peak) inverse and 30 M.A. (milliamperes) continuously, and at 120 Kv.P. (inverse) and 1000 M.A. (D.C. equivalent) for short periods.

With the latter load the voltage drop is claimed to be approximately 250 volts, which quantity is negligibly small. The filament rating ranges from 12.0 to 16.0 volts and 11.8 to 14.0 amperes.

One type of rectifier manufactured by the Eureka Tube Corporation is designated as *EV-10-140*. This tube is designed to operate in air with a maximum inverse potential of *140 Kv.P.* and *30 milliamperes* continuously. Because the valve is provided with a cylindrical shell of molybdenum anode surrounding the helical tungsten cathode filament no undesirable charges due to stray electrons will accumulate on the glass envelope, a feature char-

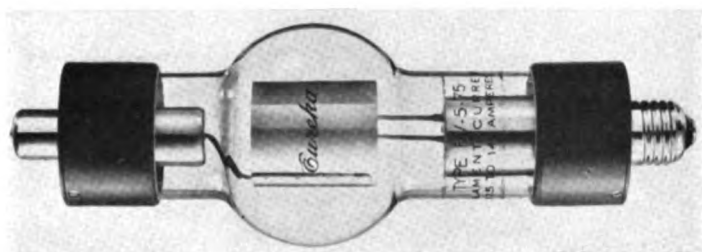


Fig. 22. The Eureka EV-5-75 Valve To Operate Oil Immersed.

acteristic of all *Kenotron* valve tubes. The filament characteristics of the *EV-10-140* is 12.0 to 14.0 amperes at 12.5 to 16.0 volts.

Of the Eureka series, another valve-tube, designated as *EV-5-75*, is of particular interest as it operates in oil in either the vertical or horizontal position at an inverse voltage not exceeding *140 Kv.P.* and *50 M.A.* continuously on a full-wave circuit. When used on a half-wave circuit, the milliamperage rating is halved, i.e., only 25 milliamperes at the maximum given voltage should be employed. The filament of the valve is energized by 12.5 to 14.0 amperes at 9.6 to 11.3 volts.

A high voltage kenotron, *model KR-5*, shown in Fig. 23, is designed to operate on 800,000-volt installation. For operation in all types of rectification circuits except that of a constant potential type, the *KR-5* has a rating of *250 Kv.P.* maximum inverse voltage and *500 M.A.* maximum current for short-period loads, and *50 M.A.* for continuous operation. When connected in a constant potential circuit, the tube can withstand *215 Kv.P.* maximum inverse kenotron voltage. Its filament rating is 7.0 to 9.5



Plate X:—The G.E. Portable X-Ray Unit In Preparation For Examination of the Welded Pressure Vessel.

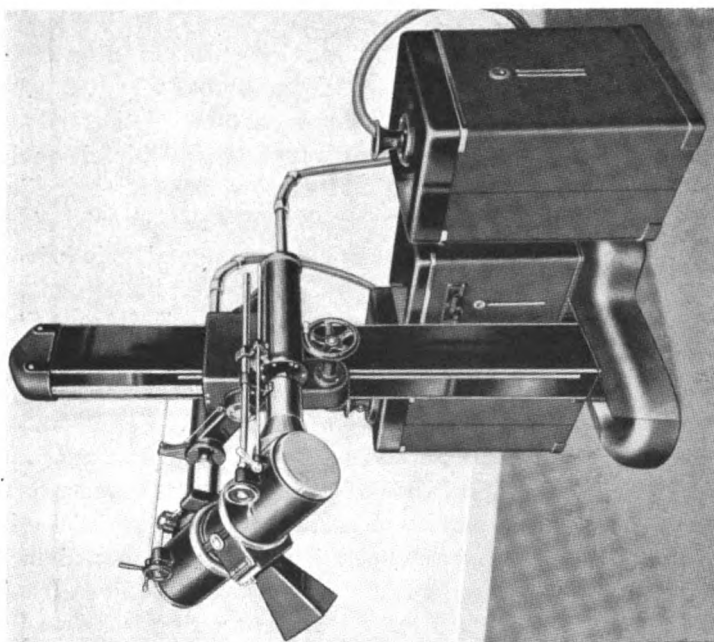


Plate IX:—The Keleket 220-KV Industrial Unit Equipped With Localizing Diaphragm.

volts and 11.5 to 14.0 amperes.

There are on the market a great many varieties of thermionic rectifiers manufactured by various manufacturers. Though differences exist in the design and construction of these tubes, in principle they all embody the same thermionic emission features of the kenotron tube.

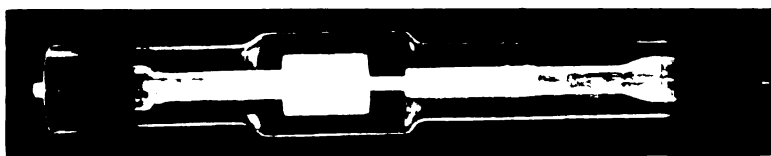


Fig. 23. KR-5 G.E. Kenotron for Use in 800,000-Volt Installation.

Among rectifying tubes of most recent origin, one of the most remarkable is the new Philips valve-tube, Fig. 24. This is a gas-filled multiple-discharge high tension rectifier. It consists of an oxide-coated cathode and a cylindrical cup-shaped anode sealed respectively into the opposite ends of a tubular vessel, which contains metal intermediate discharge cells, numbering from six to nine, depending on the type. The valve, after having been highly evacuated, is filled with a minute quantity of mercury vapor, which maintains a tube pressure equivalent to the vapor pressure of mercury at room temperature.

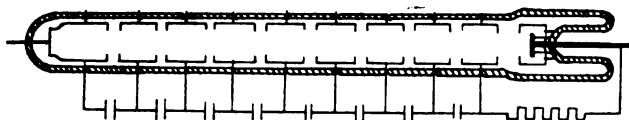
The tube is surrounded by a number of cylindrical condensers arranged in series, and each is connected in parallel with the individual cells or discharge stages, with the exception of the first stage at the cathode end which is shunted by a high resistance.

The purpose of the condensers is to maintain an equal distribution of potential across the successive stages. Another important function of these condensers is to prevent a possible electrical disturbance, in the starting of the discharge, influenced by the intense electric field due to the portions of the consecutive discharge cells exposed to the air.

Valves of this design have been constructed to maintain an inverse constant potential of 225 kilovolts and are well adaptable for multi-stage x-ray generators rated at a million volts or over. The oxide coated filament takes about 8 watts, and its temperature range is normally limited to a variation from 15 to 45 degrees centigrade. Owing to the large emission properties of the "dull

emitter" filament, the voltage drop across the tube when carrying a maximum current of 1100 milliamperes is only about 40 volts.

Rectification of the current to the x-ray tube may be achieved by connecting the valves either in the primary or in the second-



(a) Sectional View of Philips Valve.



(b) The Commercial Form of the Tube.

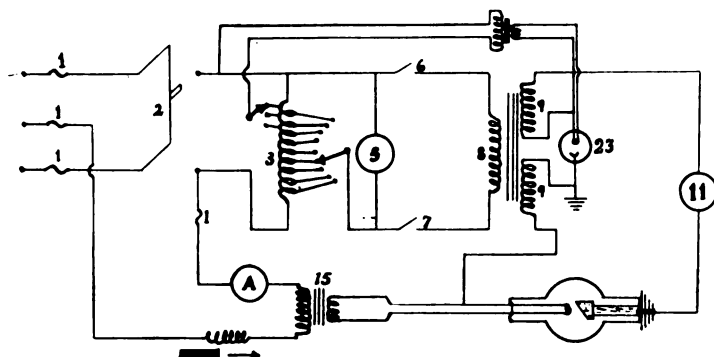
Fig. 24. Philips Gas-Filled Rectifying Valve.

ary circuit of the x-ray transformer. The general trend, however, has adopted the latter arrangement because, aside from other advantages, the inverse voltage across the x-ray tube is relieved by the amount sustained across the x-ray tube, viz., one-half of the inverse voltage of the x-ray tube is suppressed by the valve, and the other half by the x-ray tube, in a single valve rectification circuit.

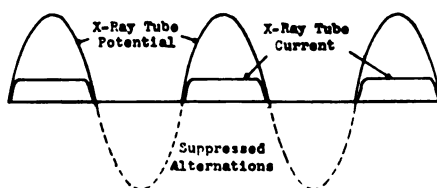
(1) SINGLE VALVE RECTIFICATION.—(a) *Half-Wave Pulsating Circuit*.—The simplest valve rectified circuit involves a kenotron (23) connected in series with the x-ray tube, shown in (a) of Fig. 25. In this type of rectification, when the direction of the current is from the cathode to the anode of the valve, the voltage drop is chiefly across the x-ray tube. But, when the current reverses its direction in the next alternation, the inverse potential from the transformer secondary is equally divided between the valve and the x-ray tube. Thus, the current passes across the x-ray tube during one-half of the cycle and is suppressed during the next alternation. The actual current passing through the x-ray tube, therefore, has half-cycle, unipolar, and unidirectional wave form, as given in (b) of Fig. 25. The process is known as *half-wave rectification*.

On a half-wave circuit, a radiograph made with an exposure time of, for instance, $1/20$ second at 25 M.A. meter-reading, the x-ray tube actually received 50 M.A. during every other alterna-

tion of the current. This is due to the fact that a counter-electromotive force and hence a counter-current is produced in the transformer secondary during that one-half cycle of the current which is suppressed from the x-ray tube, and which current is



(a) Circuit Diagram of a Single Valve Unit.



(b) Approximate Potential and Current Wave Forms.

Fig. 25. Single-Valve Half-Wave Rectification.

supplemented to the next half-cycle allowed to pass through the x-ray tube. Thus, only one-half of the number of transformer secondary impulses, each having a current magnitude twice that of a normal impulse of 25-milliamperere value, are delivered to the x-ray tube.

With a 60-cycle current at full-wave rectification, for instance, an exposure of 1/10th of a second duration is equivalent to 12 impulses, 1/10th of 120 impulses or alternations, and the x-ray tube will receive 12 impulses. In the case of a half-wave rectified circuit, however, the tube will receive, for the same exposure time, 6 impulses but at twice the milliamperage indicated on the milliammeter. Though the exposure time and hence the milliamperere-seconds are the same in both cases, a tube which is not designed to operate on half-wave current will be subjected to additional strains with consequent shortening in its life.

(b) *The Villard Circuit*.—One of the oldest yet now most popular x-ray circuit is the voltage-doubling one, first applied to practice by Villard.

This type of circuit, illustrated in Fig. 26, comprises a valve tube connected to the transformer terminals through two condensers arranged in series. In parallel with the valve tube is an x-ray tube connected in opposition with the former. Since this

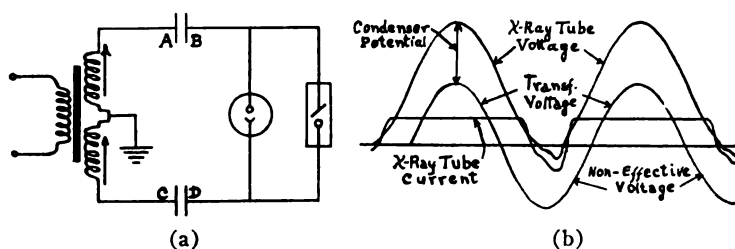


Fig. 26. Diagram of a Villard Circuit.

arrangement supplies the x-ray tube with double the potential of the transformer secondary, the valve must be capable to withstand the maximum tube tension (voltage) without breakdown. In view of the latter position of the valve tube, circuits of relatively high tension employ two valves in series across the transformer.

During the first half cycle when the current runs in the direction indicated by the arrows, the valve becomes energized. As in this alternation the electrons flow toward the plate *A* it becomes negatively charged while the plate *C* becomes positively charged. The concentration of the electrons at the plate *D*, however, is influenced (increased) by the positive charge on *C*, charging *D* negatively with respect to *C*. Similarly, the plate *B* becomes charged positively in a magnitude equivalent to that on plate *C*. Thus, each condenser becomes loaded with approximately one-half the transformer voltage during the rising potential wave. The inverse potential across the x-ray tube is then equal to that across the valve, and is constituted by the voltage required to pass charging current across the condensers. The condensers continue to supply current to the x-ray tube during the falling of the voltage wave except during the short interval of inverse potential.

As the transformer polarity is reversed, the condenser voltages, supplemented by that of the transformer, are impressed on the x-ray tube with the rising potential wave. The current through

the x-ray tube is maintained while its potential is falling back to zero. Thus, the voltage across the x-ray tube pulsates at twice the transformer potential and at the same frequency of the alternating current through the secondary circuit. The approximate wave-forms of the respective voltages and the tube current are depicted in Fig. 26b.

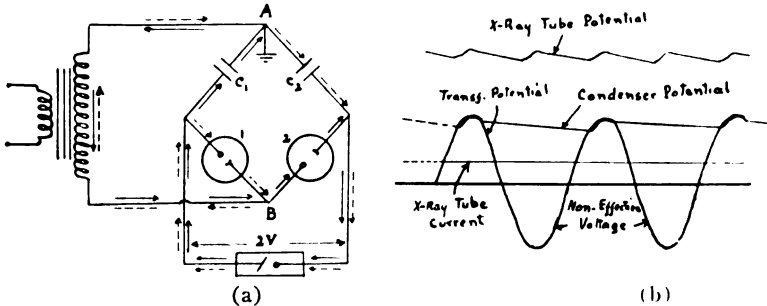


Fig. 27. (a) Greinacher Circuit, and (b) Wave-Forms of the Voltages and the Current.

(2) TWO-VALVE RECTIFICATION.—*Constant Potential Voltage-Doubling Circuit (Greinacher).*—A constant potential circuit which has found favorably large commercial application in industry is the one suggested by Greinacher.

Two valve-tubes connected in series with each other and with two condensers of fairly large size form a bridge arrangement with respect to the transformer secondary and to the x-ray tube, shown in Fig. 27.

One terminal of the transformer connected at A between the two condensers is grounded so that the tension at B alternates from the maximum of one polarity to that of another polarity. The x-ray tube, having been connected across the outer plates of the condensers, is energized at twice the transformer potential constituted by the combined potentials of both the transformer and the respective condenser.

In operation, if the direction of the first half-cycle of the current through the transformer secondary is, for instance, from A to B, the valve-tube 2 becomes conducting, and charges the condenser C_2 to the full transformer voltage. The x-ray tube, then, receives the entire transformer potential plus that from the condenser C_1 charged from a previous half cycle—a total of approximately double the voltage of the transformer.

As the current reverses its direction (indicated by the broken arrows), the transformer voltage supplemented by that of the condenser C_2 drives the current through the x-ray tube, then through valve 1, and back to the positive terminal B of the transformer. Thus, a continuous current is maintained through the x-ray tube while the transformer current alternates twice.

While the valve-tube 1 is conducting, the condenser C_1 becomes fully charged to the same potential of the transformer. Hence, the flow through the x-ray tube continues, drawing current alternately from each of the condensers. The wave-forms are depicted in Fig. 27b. This circuit renders itself valuable from the standpoint of economy in adequate insulation of the transformer secondaries from ground, and that owing to the presence of condensers in the circuit the transformer may be made smaller and hence more compact.

During the first alternation of the current which passes through the x-ray tube, the condenser which is in parallel relation with the x-ray tube becomes fully charged at the crest of the transformer potential wave. But, as this potential starts to fall, a difference of potential builds up across the valve tube, and the reduction dV in condenser potential which sustains the x-ray tube at a constant-potential current is given by the relation

$$dV = - \frac{i \cdot dt}{C} \quad (48)$$

where, i is the x-ray tube current maintained by the condenser having a capacitance C given in farads, and dt is a fraction of the condenser discharge time in seconds for an electrical time interval corresponding to dV .

It is well to mention here that a series of Greinacher circuits can be cascaded together to produce voltages ranging from 150 KV to one million KV or over. The tube voltage, however, will be limited only by transformer insulation problems.

(3) FOUR-VALVE RECTIFICATION.—(a) *Full-Wave Gratz Circuit*.—One of the most popular circuits for obtaining full-wave rectification at full transformer potential is that employing four valve tubes, shown in Fig. 28. The circuit, first suggested by Gratz, has bridge arrangement, in which two valves function dur-

ing one-half of the cycle and the other two during the other half.

When the current in the transformer secondary runs from *A* to *B* the valves 1 and 2 become conducting, and the current passes through the valve 1, the x-ray tube, the valve 2, and back to the

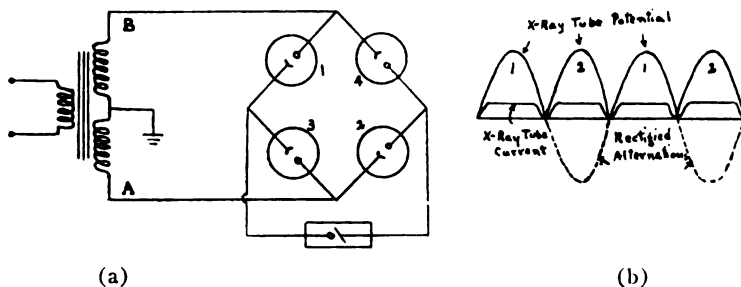


Fig. 28. Four-Valve Gratz Circuit.

transformer, as at *A*, whereas the valves 3 and 4 are non-conducting. The first half-cycle, marked by 1 in Fig. 28b, is thus permitted to pass through the x-ray tube. As the current reverses its direction, it flows from *B* to *A* in the transformer, and passes through the valve 3, the x-ray tube, the valve 4, and back to *B*, allowing the second half of the cycle, marked by 2 in Fig. 28b, through the x-ray tube.

While all four valves take part in delivering current to the x-ray tube during one complete cycle of the current, it is obvious that only two valves are energized at a time. The operation thus continues supplying current to the x-ray tube alternately through each respective pair of the valve-tubes during the entire duration of the x-ray exposure.

The Gratz circuit may be arranged to serve a dual purpose. This is accomplished by providing a double-throw switch between the valve tubes on one side of the bridge and the ground lead from the center point of the transformer. When this switch is in "off" position the circuit functions as Gratz connection, and, when it is in "on" position it connects the anode of the x-ray tube to the center of the x-ray transformer, and simultaneously disconnects the current to the filaments of the valves connected on the same side. A full-wave current at one-half the normal voltage of the transformer secondary can be secured with this arrangement. The wave-forms of the voltage and the current of this type of rectifica-

tion are similar to those depicted by 28b. Such a circuit is of especial advantage when a high milliamperage technique at relatively low voltage is desired, as in x-ray diffraction work.

(b) *400-KV Constant Potential Circuit.*—A circuit arrangement employing four valve-tubes and two charging condensers each in series with a 100,000-ohm resistor and two valves in the transformer circuit is given in Fig. 29. The energizing circuit is center-grounded so that spacings for only 200,000 volts to earth are required when operated with a 400,000-volt Coolidge x-ray tube.

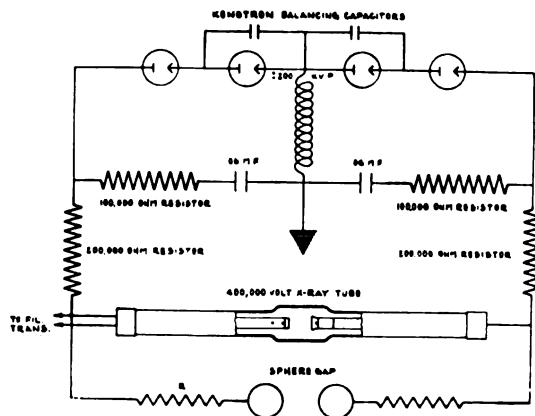


Fig. 29. 400,000-Volt and 5-M.A. Constant Potential Circuit.

The essential characteristic of the equipment centers around the inclusion of sufficient electrical impedance in series on either side of the x-ray tube. The importance of this procedure cannot be over-emphasized, as in the absence of this resistance the instantaneous current and voltage surges may be accompanied promptly by instability in tube performance. This is one of the chief reasons why earlier constant potential equipments of the type have failed to function properly. Experience has shown that a resistance of at least one ohm per volt of the x-ray tube potential must be included in that portion of the circuit which is in series relation with the x-ray tube. The two resistances of 200,000-ohms each on either side of the x-ray tube are shown in Fig. 29.

It should be further noted that a means must be provided for gradually raising the high tension to be applied to the x-ray tube

in order to avoid a sudden application of the full transformer voltage to the x-ray tube when the x-ray switch is turned on. That is, the x-ray tube voltage should be raised gradually to its full value. Another factor of great importance is the provision of a protective sphere-gap connected in parallel across the x-ray tube. This serves to discourage the growth of over-voltage surges as well as to carry out voltage measurements when desired. It further enables the calibration to be made on the equipment from time to time.

(4) **THREE-PHASE SIX-VALVE CIRCUIT.**—For over a decade, roentgen generators furnished with six valve-tubes have been used with satisfactory results, but the scheme has not become generalized in view of the cost of the equipment, difficulty in securing a multi-phase and high-frequency current source at any desired location where the apparatus is to be operated, and, above all, the advantages realized with this type of circuit seem to have no practical bearing on the quality of a radiograph.

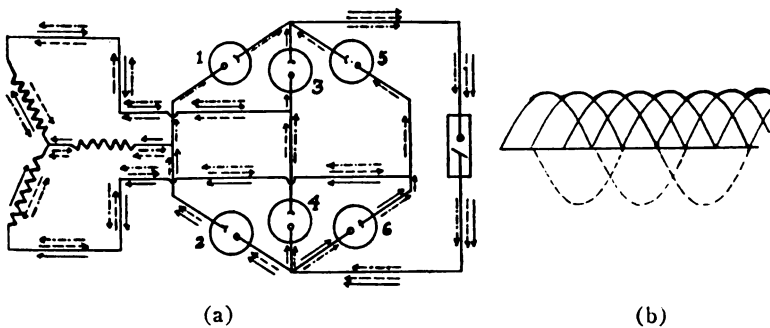


Fig. 30. (a) Six-Valve Circuit Employing Three-Phase Current, and (b) The Wave Form of The Voltage.

If a three-phase supply source is available, a star-connection may be applied to a six-valve circuit arranged so that each pair of valves will conduct current equivalent to a single-phase supply. The adoption of such an arrangement appears to be the logical sequence if the radiographic exposure technique called very frequently for high-speed exposures, that a sacrifice in tube life as a result of high tube current together with the cost of equipment and maintenance are of no particular concern.

Though a mechanical rectifier employing a split-phase arrange-

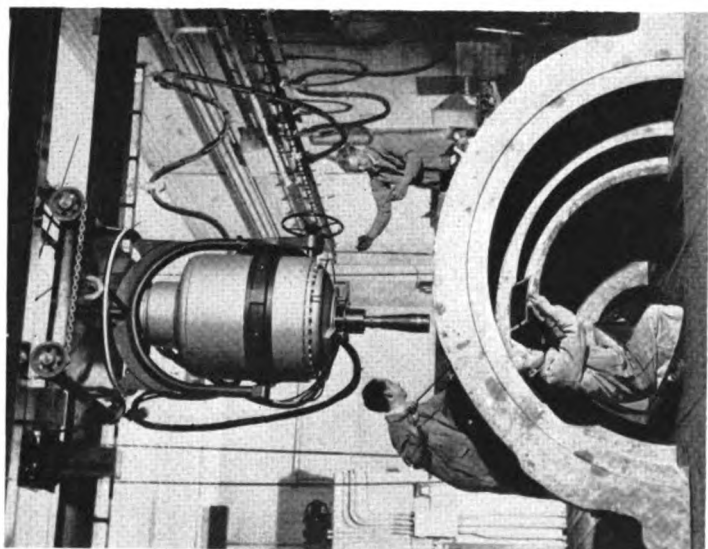


Plate XII:—Affixing a Loaded Cassette for Radiographing a Thick Steel Casting With the One-Million-Volt X-Ray Unit.

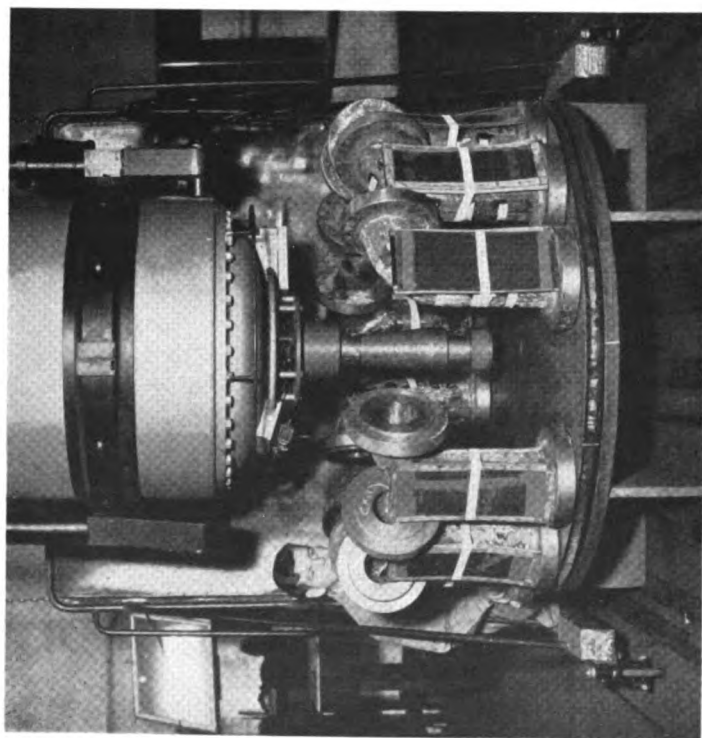


Plate XI:—With the G.E. Million-Volt X-Ray Unit, Shown Above, a Number of Individual Castings May Be Radiographed Simultaneously With a Single Exposure.

ment may prove more advantageous from a standpoint of economy, the adoption of the valve-tubes in such multi-phase circuits is of special interest, owing to the high operating efficiency and the extreme flexibility afforded by the modern valve-tube through its carefully designed construction with relatively long tube life.

A three-phase circuit employing six valves and giving an approximation of constant potential with less than 1.2% ripple is illustrated in Fig. 30.

In this circuit, the x-ray tube is connected across the valves, which are arranged in pairs and in series relation to the x-ray tube. The latter receives (in a 60-cycle per phase circuit) one impulse per 1/6th of a second, or 360 impulses per second, each valve conducting one-third of this number. Since there is a phase difference of 60 electrical degrees between each two consecutive impulses, if, for instance, the valve 1 conducts current to the x-ray tube, the valves 4 and 6 return it to the corresponding coils of the transformers; and, if the valve 3 is conducting current to the x-ray tube, the valves 2 and 6 return it to the respective phase windings, and so on.

As individual phase lines furnish equal potentials, V , for instance, the maximum tension sustained across the valves as well as the x-ray tube is the vector sum of any two individual phase voltages of the mains supply, i.e., a total of $\sqrt{3} V$. But, due to the capacity effect produced by the cables, x-ray and electrical protection shields, etc., the tendency of this to increase as high as 16%, or to $2V$, with the x-ray tube current at a minimum limiting value is well indicated.

To insure against overload, the x-ray practitioner frequently loads the x-ray tube at 65% to 80% of the maximum permissible rating, resulting in a sacrifice of the advantages gained through the use of a six-valve three-phase apparatus. Consequently, from the foregoing discussion, the question whether or not the adoption of the latter circuit to industrial diagnostic equipment is superior to that furnished with four valves remains open subject to some further advance yet to be made in this direction.

(5) THE GENERAL ELECTRIC 1,000,000-VOLT INDUSTRIAL X-RAY UNIT.—With recent introduction of the one-million-volt

x-ray generator emanating from the laboratories of the General Electric X-Ray Corporation a far-reaching stride of supreme significance to the industry as well as to science has been achieved. The development and subsequent rigid operative tests of this contribution have been in progress for nearly four years to provide the present requirements that primarily demand high speed methods of inspection especially of heavy parts, welded seams, high pressure boilers, concrete constructions, power turbines, fly-wheels, etc., which have required exposures up to ten hours with prevalent apparatus employing lower tensions, and which exposures now have been reduced to a few minutes by the use of this new development.

With the existing equipment operating on 300 KV to 400 KV it is possible to radiograph steel respectively 4 inches to $5\frac{1}{2}$ inches in thickness, preferably employing an oscillating Bucky grid to minimize the effect of the secondary radiations. But, with the advent of the G-E million-volt machine, steel up to 9 inches thick at a focus-film distance of 32 inches can be radiographed in surprisingly short exposure time, which prevails between $1/35\text{th}$ to $1/120\text{th}$ that employed with 400-KV unit. The technique involves the use of a lead filter up to $1/4$ inch in thickness placed between the film and the cassette, with a d/t ratio between 10 to 20 for optimum results, in which ratio d is the *focus-film distance* and t is the *thickness* of the material radiographed.

While with low tension apparatus the disclosure of cracks of the order of $1/2$ inch in 4-inch steel weld would be considered as fair, the sensitivity of the million-volt machine in detecting small defects is $1/8$ inch per 6-inch thickness. At $6\frac{1}{2}$ -inch thickness of the plate, the sensitivity of the unit is equal to that of the 400-KV machine employing a Bucky on a part less than 5-inch thick.

The design and the construction of this new device may be explained by reference to pertinent illustrations and especially to the diagram shown in Fig. 31. The most outstanding feature of the development resides in its unique design of the multi-section x-ray tube concentrically mounted within a 180-cps (cycles per second) resonance transformer, whose secondary is tapped to supply the individual discharge cells of the tube with appropriate voltages. Owing to this arrangement, provision

of necessary protection against high voltage surges is amply accomplished. The assembly is integrated in a metal housing which, having been completely depleted of air and moisture, is filled with Freon, a gas of high insulating properties, and then hermetically sealed.

Aside from increased voltage characteristic of the unit, the multi-section feature of the x-ray tube permits the distribution

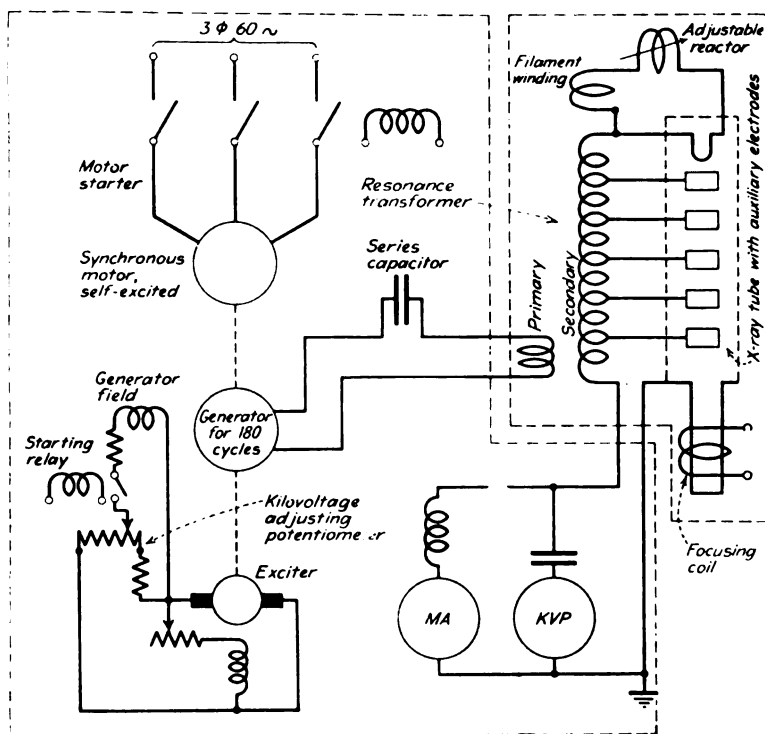


Fig. 31. Simplified Wiring Diagram of the G.E. Million-Volt X-Ray Generator Unit.

of the total potential across the successive sections or stages intermediate to the cathode and the anode, thus restricting the potential gradients to safe limits. Relatively high but consistent electron-emission properties of the hot cathode affords the generation of high intensity x-ray radiation of such characteristics that scattered radiation is minimized. Thus, majority of the materials of high density can be radiographed without recourse

to time-consuming shielding or blocking. Consequently, not only saving of time and labor is insured, but the speedy inspection of important production is made possible.

The electrons from the cathode as they pass the last discharge cell of the multi-sectional tube, shown in Fig. 32, are caused, by means of a focusing coil, to converge to a point focus on the target which is at the end of a tube continuous with the multi-stage chamber and projecting outward 2 feet from the x-ray tube assembly. In view of the optimum size of the focal spot (varying from 0.6 mm to 3.0 mm effective), radiographs obtained by means of this new tube possess sharp, well-defined radiographic features. Since the radiation from this point source on the target propagates in all directions, the entire circumferential seam of a boiler or a pressure vessel can be radiographed at one time.

The illustration shown in Fig. 33 depicts the use of the 1,000,000-volt x-ray tube assembly supported by a universal suspension with the target head projecting through the end opening of a boiler of about $3\frac{1}{2}$ feet in diameter.

It is well to note here that in view of the great reduction of safety factor of castings through accuracy of x-ray analysis, substitution of castings for forgings in a great many types of structures has been made possible. In an article, entitled "Ten Years' Progress in Radiography," Metal Progress, November, 1941, Mr. A. J. Moses of Combustion Engineering Company, (Hedges-

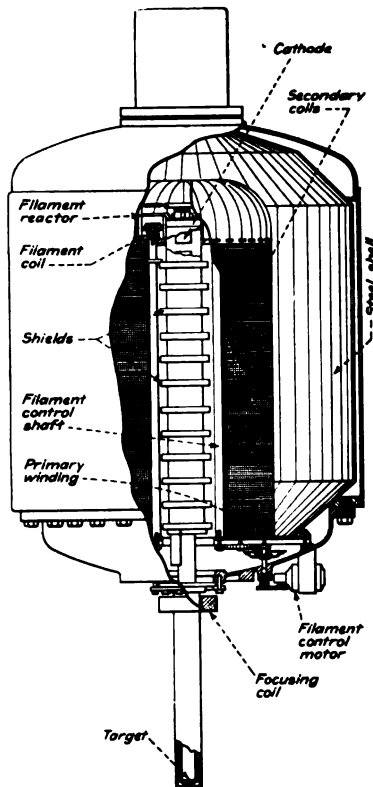


Fig. 32. The G-E Multi-Section X-Ray Tube Concentrically Mounted Within the High Voltage Resonance Transformer.

Welsh-Eidner Division), presents a comprehensive discussion on the various limitations of the prevalent low-voltage x-ray generators in the inspection of castings in a comparative respect to the various applications of the present million-volt unit. In that writ-

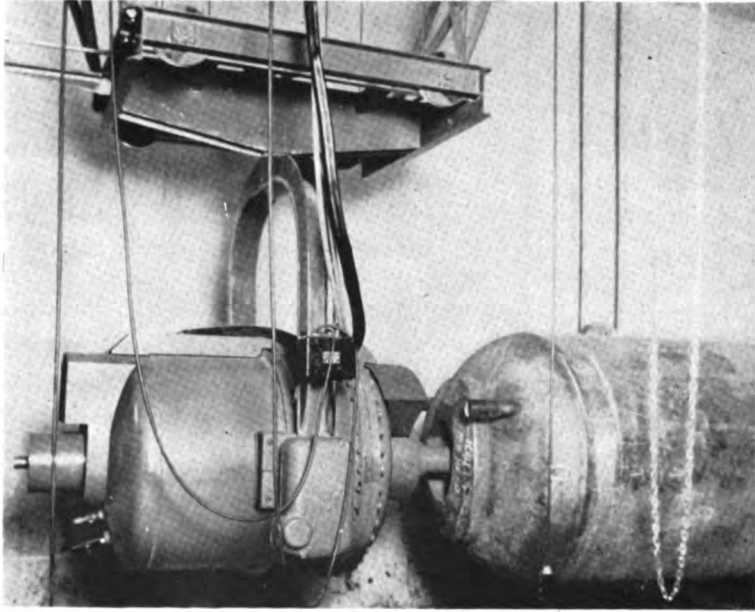


Fig. 33. The Focal Spot of the Million-Volt Tube Projecting Through End Opening of The Boiler Radiographs the Entire Circumferential Seam At One Time.

ing Mr. Moses points out, "Due to the limitations of the x-ray test, the user has been forced to go to very expensive seamless forgings. At present, the forging capacity of the country is so taken up with other work that we are being forced to weld greater thicknesses than heretofore attempted. This year, we have been fabricating some boiler drums $5\frac{1}{2}$ inches thick. With our 400,000-volt machine and the use of Bucky grid, it requires $7\frac{1}{2}$ hours to take individual pictures of these weld seams. Therefore, you can appreciate that we view the development of the 1,000,000-volt tube, which will take pictures of such thicknesses in 15 minutes, as progress of the first magnitude."

The dimensions of the unit may be given as 4 feet in length

and 3 feet in diameter with an over-all axial length, including the target projection, of 6 feet. In spite of its weight of 1,800 pounds, the unit is very flexible and can be readily moved about by means of an overhead crane for the inspection of industrial castings or welds weighing as high as 60 to 90 tons.

In operation, the target of the tube is brought next to the casting with an x-ray film appropriately affixed in position and contact print of the defect is made by exposure controlled from a lead-lined operating room adjacent to the main x-ray room. Depending on the density and the thickness of the material to be examined, the voltage is gradually brought to the desired value and the current is established for the exposure. Since the x-ray unit is self-rectifying, the current through the tube is half-wave and pulsating.

In passing, we may add that the usefulness of the million-volt unit, however, will by no means supplant the existing lower voltage x-ray generators which are adapted to render excellent service in the examination of light metals and thin sections of heavy metals in routine inspection work. The new development, indeed, rendering the use of x-rays more complete, has already become an indispensable component of the prevalent x-ray apparatus.

(6) A CASCADE GENERATOR IN EXCESS OF ONE-MILLION VOLTS.—The principle of cascading Villard circuits to obtain high voltages limited only by the transformer output potential has long been adopted by the industry or research laboratories. The point of interest in this type of circuit lies in that when the number of valve tubes is increased beyond four, a high frequency method of filament heating becomes preferable from the standpoint of constructional simplicity, insulation of the equipment, and of the preclusion of all accessory units.

A six-stage generator employing 12 rectifying valves to produce 1,250,000 volts is shown in Fig. 34. The unit employs a transformer supplying a potential of 120 *Kv.P.* at 200 cycles, and 12 gas-filled rectifying valves, each rated for an inverse potential of 225 kilovolts. Intermediate to the valves are condensers each having a capacity of $0.01\mu F$ (depending on the frequency of the current) at an operative voltage of 240 *KV*.

The filaments of the valves are heated from a high frequency

valve generator furnishing approximately 8 watts to each valve tube. This energy is transferred to each filament at a frequency

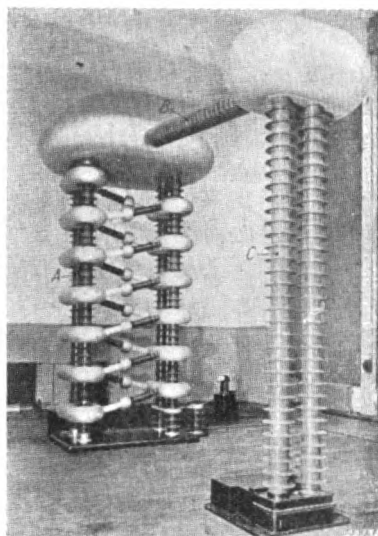


Fig. 34. Bouwers' Six-Stage 1250-KV Generator.

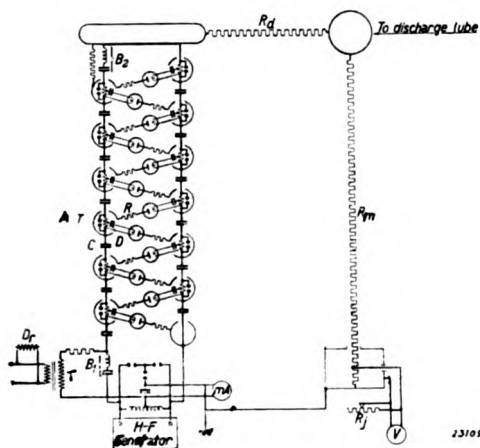


Fig. 35. The Circuit Diagram of 1250-KV Six-Stage Generator.

of 500,000 cycles through a series-connected condenser and a small autotransformer inserted between consecutive condensers. A damping resistance in series with the anode of each valve serves

to prevent a possible short-circuit between the two groups of condensers on each side of the valve. An additional condenser connected in series with one lead of each filament is employed to further prevent radio interferences that may otherwise radiate from the apparatus.

The lowest portion of the apparatus must be capable to sustain an insulation against *120 Kv.P.* (the transformer potential), and the impedance in the upper portion of the apparatus should be insulated for *1250 KV*, the generator output. Two protective high-ohmic resistances are inserted on either side of the x-ray tube to stabilize abnormal voltage surges. The height of the room to accommodate this apparatus should be at least 7.5 meters from the ground.

By connecting two such generators in series, one producing a positive potential of 1500 kilovolts to earth and the other a negative potential of equal magnitude, a potential difference of 3,000,000 volts can be easily realized. Increasing the number of stages, then, tensions as high as 5,000,000 volts (2.5 million volts negative, and 2.5 million volts positive, both against earth) should be feasible. The space required for a generator of this character, without supplementary screening means, must have minimum dimensions of 14 x 14 x 28 meters.

CHAPTER IV

X-RAY TUBES

The introduction of a highly evacuated discharge tube in the year 1879 by William Crookes, an English physicist, lay the basis for discovery by Roentgen, in the year 1895, the radiation which we have previously referred to as *x-rays*. The development further marked the first stride in the advent of the ever-hailed modern high-power x-ray tubes.

Subsequent to the discovery of x-rays, the first x-ray tubes to be developed for general use were *gas-tubes*. A gas tube consists of a bulbous envelope with two electrodes sealed in the two glass arms on opposite sides of the bulb and respectively forming the anode and the cathode of the tube. A vacuum-regulating device comprising a few layers of mica, or activated charcoal, is provided for automatically adjusting the gas pressure inside the tube during operation.

The operation of a gas tube depends on the ionization of the residual gas in the tube. The gas is obtained by first highly evacuating the tube and then allowing a minute amount of an inert gas to be absorbed by the regenerator of charcoal, mica, or asbestos located in a separate side tube, during processing of the tube. This procedure raises the tube pressure between 0.001 mm to 0.01 mm of mercury. When a high voltage is applied to the tube, the gaseous molecules dissociate into *electrons* and *positive ions*, the positive ions moving to the cathode and the electrons accelerating toward the anode. These electrons constitute the *cathode rays*, whose speed is dependent on the impressed voltage; and, upon their impact on the anode surface or the target they produce *x-rays*.

The cathode of a gas-tube consists of an aluminum or molybdenum rod with an enlarged terminal having a concave surface which serves to focus the cathode rays on the center of the anode surface facing the cathode. This central area on the surface of the anode is called the *focal spot*.

Because a discharge from an alternating current source can pass to either direction in a gas-tube, the latter is operated

generally on a rectified unidirectional potential so that the x-ray producing properties of the tube will not be defeated.

In a gas-tube, since the magnitude of the current and the velocity of the electrons are dependent on both the residual gas pressure and the potential applied to the tube, a complete control over the intensity and the penetration quality of the resulting x-rays independently of each other has not been practicably possible to achieve. Recourse has been made, therefore, to the development of a new type of x-ray tube with more consistent electron discharge properties.

The new departure is a *high vacuum tube* having a tungsten filament cathode which, when heated to a high temperature, furnishes a copious stream of electrons also known as cathode rays. The principle, whose commercial application was first announced in the year 1913 by W. D. Coolidge, is known as *thermionic emission*. An x-ray tube of this type is called a *thermionic tube*, or, an *electron tube*.

The cathode of the electron x-ray tube consists of a spiral tungsten filament surrounded by a concave molybdenum focusing element. From this element the electrons are projected toward the massive copper anode and focused on a tungsten disc located in the center of its surface facing the cathode at an angle ranging between zero and 45 degrees with the long axis of the tube. The area on the tungsten disc which is bombarded by the cathode rays when the tube is energized is called the *focal spot*, as in the gas-tube. The effective dimension of the focal spot varies from 0.3 mm to 6.0 mm square for ordinary radiographic tube, and larger for other types of applications. The focal spot is usually visibly defined as an etched area in the center of the tungsten disc.

The *current* through the x-ray tube is dependent on the number of electrons emitted from the filament, which amount in turn *is dependent on the temperature of the filament*. The higher the temperature of the filament the greater is the current passing through the x-ray tube. The quantity of the current (which is usually measured in milliamperes) across the tube is dependent both on the temperature and, within some extent, on the magnitude of the applied voltage. This property of the electron tube, then, is a distinct advantage over that of the gas-tube

in that the *electron emission* (cathode rays)—and hence, the milliamperage through the x-ray tube—can be accurately *controlled by the temperature* of the cathode filament, whereas the *quality* (penetrating power) of the *x-rays* produced can be *controlled* to a high degree of consistency by regulating the *impressed tension* on the tube. Thus, the penetration quality and the intensity of the x-rays from an electron type x-ray tube can be controlled independently of each other. This new development lends itself to the use of load capacities ranging from 1.0 to 200 kilowatts, while the load capacities of the old type gas-tubes seldom have exceeded one kilowatt.

Among numerous and varied modifications of the modern electron x-ray tube are tubes with various focal spot shapes and sizes, stationary and rotating-anode tubes, non-shock proof and shock-proof tubes, non-ray proof and ray-proof tubes, and tubes having air-cooled radiators, water-coolers, oil-coolers, or a combination of water and oil coolers, for their cooling system.

Cooling the x-ray tube is very essential, as it becomes extremely hot during operation as a result of the bombardment of the anode surface (target) by high energy cathode rays and the subsequent conversion of the most part of their energy into heat at the target. Indeed, one single tube of any construction mentioned above may be so designed by proper choice of a cooling system that it may be employed for more than one purpose.

1. The Universal X-Ray Tube.—The earliest electron type x-ray tube which employed a hot-filament cathode is the one known as the *universal tube*, owing to the fact that a single tube of this character serves, where necessary, for radiography, fluoroscopy, and, in medical work, for therapy.

A universal x-ray tube consists of a glass envelope with a central bulbous portion enclosing the cathode and the anode. The cathode has a spiral tungsten filament welded permanently to the apex of an electron-spreading cone, which is surrounded by a molybdenum focusing shield to direct the beam of cathode rays to an accurately predetermined area (focal area) on the target. The target is of solid tungsten, and during operation of the tube it becomes heated to incandescence, since no direct provision is made for conducting the heat away from the metal.

Tungsten is adopted universally as the target material because of its having a high melting point, high atomic number, and low vapor pressure.

The universal tube is designed to operate on rectified current only, since both electrodes are hot during operation, and therefore, are sources of electrons. While the tube may be operated

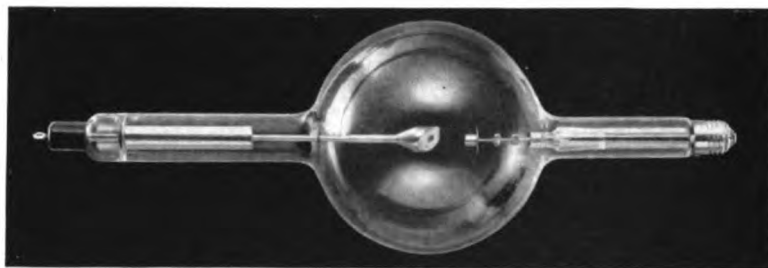


Fig. 36. A Universal X-Ray Tube.

with small impressed loads over long periods of time, it is seldom used for radiographic work of considerable volume, in view of the adaptation of the line-focus design for this latter purpose.

A universal tube which is designed to operate continuously at 140 *Kv.P.* and 5 *M.A.* with a filament characteristic of 3.5 to 5.0 amperes at 4.0 to 8.5 volts is shown in Fig. 36.

Another tube of similar design to operate at 220 *Kv.P.* and 30 *M. A.* continuously, and having its filament cathode incorporated in a hemispherical shield, achieves a better control of the cathode rays with an x-ray intensity approximately six times that given off from an ordinary universal tube. The tube is shown in Fig. 37.

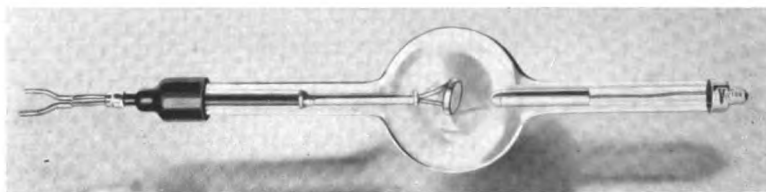
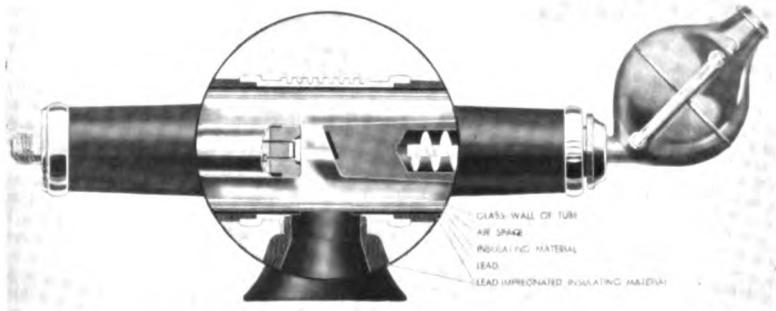
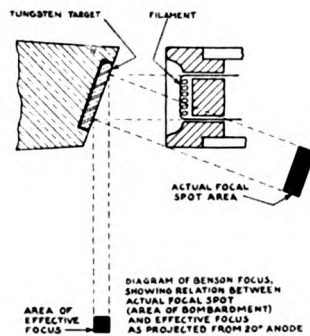


Fig. 37. Water-Cooled G-E X-Ray Tube Rated at 220,000 Volts and 30 Milliamperes.

2. Diagnostic X-Ray Tubes.—For diagnostic work of optimum quality, an x-ray tube having a *line-focus*, or *band-focus*, design, Fig. 38, lends itself to maximum use in industrial radiographic work. While some tubes of this type are employed for intermittent use because of the limitations imposed by their



(a) Water-Cooled X-P Coolidge Tube.



(b) The Diagram of the Line-focus.

Fig. 38. The Diagnostic Tube with Line-focus Construction.

cooling system (which consists of air-cooled radiators), continuously cooled diagnostic tubes are more preferable for routine radiographic practice. The cooling system of the latter type of tubes consists of water or oil circulating, by means of a pump pressure, through copper tubing carrying the liquid in and out, from the anode stem directly behind the target.

A sealed-off x-ray tube for use at 500,000 volts constant potential with ray-proof construction was introduced by the General Electric Company several years ago. The tube, shown in Fig. 39, has an over-all length of 60 inches and is designed for operation in air at a tension of 400,000 volts. The energizing equipment



Fig. 39. G-E X-Ray Tube Rated at 400,000 Volts.

is center-grounded so that spacings for only 200,000 volts to earth are required.

Tubes rated at 400 KV are also available through Philips Metalix X-Ray Corporation, Siemens-Pantix (British), Westinghouse X-Ray Corporation, Machlett Laboratories, and by Kelley-Koett Manufacturing Company. The latter firm has developed a self-contained 400,000-volt unit which combines compactness and flexibility of use. It can be used effectively for radiographing steel from $\frac{1}{2}$ inch to 5 inches thick. It has a range of voltage control between 150 kilovolts to 400 kilovolts. The 400-KV industrial unit and its control are shown in Plates IV and V.

An unique design of special interest is an industrial x-ray tube offered by Machlett Laboratories. The tube, commercially known as *Thermax*, Fig. 40, consists of a pyrex glass insert permanently mounted in a hermetically sealed oil-filled shock-proof housing. It has a line focus with an effective area of 2.3 mm square mounted at a 20-degree target angle. For continuous operation, the *Thermax* has ratings of 150 Kv.P. at 6 M.A., and 100 Kv.P. at 11 M.A. The tube is adaptable to Villard circuits, constant potential circuits, three-phase circuits, and to other half-wave rectification systems.

Owing to a special cooling system embodied in the *Thermax*, it lends itself to maximum efficiency of heat transfer; and thus, the incorporation of 2.3 mm focus has been possible. Completely surrounding the tube is a rectified insulating oil cooled

by means of water circulating, at ground potential, through corrugated copper coils which make connections through flexible ducts to the ordinary tap-water system. This water is supplied by a magnetically operated valve that when the main x-ray switch is turned on it simultaneously starts the water circulation through the system. The inherent x-ray filtration of the tube

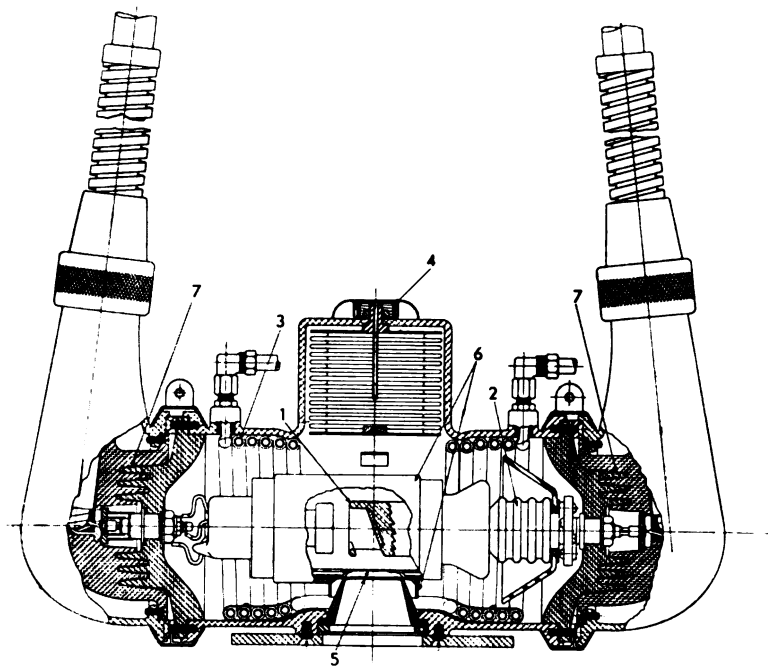


Fig. 40. The Thermax, Rated To Operate at 150 Kv.P. and 6 M.A. Continuously.

is equivalent to 0.5 mm aluminum, of which the pyrex envelope contributes 0.37 mm, the oil 0.05 mm, and the plastic x-ray window contributes 0.08 mm.

Identical with load capacity of *Thermax* is another tube of commerce available through Eureka X-Ray Tube Corporation. The tube, known to the industry as *Therograph*, is adapted to operate continuously on full-wave rectified current at 150 Kv.P. and 6 M.A. with an inherent filtering characteristic equivalent to 0.5 mm of aluminum.

The tube, shown in Fig. 41, embodies a double-focus feature

which offers the advantages of a small focus and a large focus. Provision is made so that the possibility of inadvertently overloading the filament of the small focus when desiring to use the filament of the large focus is reduced by special filament-controlling element.

Double-focus tubes are also offered by the General Electric X-Ray Corporation, Westinghouse, Philips Metalix, and others, but it appears that the use of such tubes are confined particularly to medical field. For routine industrial radiography, the use of single-focus tubes, indeed, has been found more prefer-

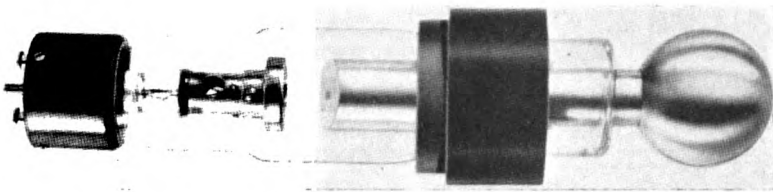


Fig. 41. The Therograph, with a Load Rating of 150 Kv.P. and 6 M.A. For Continuous Duty.

able. Owing to the rapidity with which such production is conducted the tendency to overlook the change from one focus to the other seems to militate against the advantages gained by the double-focus feature.

Completely sealed-off x-ray tubes of tensions of the order of 800 KV to 1000 KV have been developed. A one-million volt x-ray tube recently announced by General Electric X-Ray Corporation consists of *ten* intermediate discharge cells, each forming a single stage and is energized by 100 KV to reduce flash-over and insulation problems. The ten 100-KV stages, having been connected in series, produce a potential of 1000 KV . A special target built at the anode end serves to direct the x-rays to any desired point of exposure.

3. Structural Design of X-Ray Tubes.—With the introduction of the Coolidge x-ray tube in the United States in the year 1913, employing hot-cathode emission principles, an important step in the x-ray tube development was launched on its way to success. While the new tube has surmounted the difficulties and complications that have presented themselves as in a

gas-tube, whose use for diagnostic work has been gradually superseded, the problem of attaining the ideal x-ray tube has by no means been solved subsequent to the appearance of the *hot-cathode* x-ray tube.

In view of the load capacities in excess of 10 to 200 times as

great as that possessed by a gas-tube were made possible by the development of the electron tube, new problems presented themselves (1) in the provision of a means for the disposal of the tremendous quantity of heat generated at the anode, and (2) in the maintenance of the radiographic quality produced by fine focus tubes of lower energy capacities, since an increase in focal spot size was necessitated with these high power tubes. From improvements in anode design and the adequate choice of a cooling medium in an attempt to obtain more efficient heat dissipation has evolved the rotating-anode tube in the year 1929. Further improvements have given place to problems of ray-protection and shock-proofing, which have introduced still other problems.

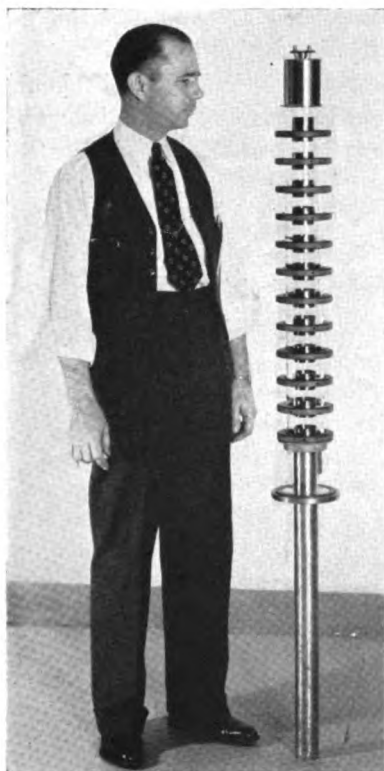


Fig. 42. The Million-Volt Multi-section X-Ray Tube.

Every x-ray tube of recent manufacture has predetermined dimensions which are largely a definite function of the maximum voltage and the maximum milliamperage at which the tube is to be operated. Owing to the desirability of high velocity electrons in the production of x-rays, x-ray tubes present problems unencountered in any other type of vacuum device, with the exception of high-voltage rectifier units.

In an x-ray tube, an atmosphere of electrons must be liberated at the cathode, projected at high velocities, focused to a small area on the target, and suddenly stopped by it. The kinetic energy ($\frac{1}{2}mv^2 = Ve/300$) of most of the electrons is transformed at the anode into heat energy, while a very small portion (less than 1%) of the energy is transformed into x-rays. Hence, the resultant heat must be dissipated. Furthermore, some of the electrons in the cathode stream after impinging on the focal spot rebound (*stray electrons*) at decreased velocities and hit the anode again all over its surface, producing *stem radiation*; and, some are attracted to the glass envelope, producing *electrostatic stresses* between the two surfaces of the glass.

Almost all x-ray manufacturers have overcome the problem of precluding the stray electrons from the glass envelope by an ingenious method which consists of a cylindrical extension from the anode, thus restricting the stray electrons to the inside surface of the cylinder. For tubes of lower tension, the preclusion of the stray electrons is accomplished by the incorporation of an earthed metal cylinder at the central portion of the tube envelope so that when the electrons bounce off the surface of the target and move toward the wall of the tube they are stopped by the metal cylinder and are conducted to the ground from it.

It is highly desirable that the electrode spacing between the anode and the cathode of an x-ray tube be as small as possible. Too close a spacing will cause cold cathode discharges and hence erratic tube operation, whereas with a large spacing difficulties are presented in the focusing of the cathode stream by reason of the increased distorting influence of the negatively charged glass envelope. The permissible variation in the magnitude of this spacing for a given tube occurs at a maximum plus or minus tolerance of 0.5 mm. Within this limit, no appreciable variation in the focal spot area or in its energy distribution is observable.

X-ray tubes of present manufacture usually have glass for envelope material, because the latter is transparent, has good electrical insulating power, a high dielectric strength, a relatively high melting point, and low x-ray absorption properties. The majority of modern x-ray tube envelopes are of *borosilicate* or *pyrex* glass. Some tubes employ *lead glass* for this purpose.

Pyrex is generally adopted because of its high mechanical strength, high melting point, and relatively high electrical resistivity.

The thickness of the glass envelope varies with the load capacity of the x-ray tube. For low voltage diagnostic industrial tubes $\frac{1}{8}$ th inch thickness will be sufficient while for voltages exceeding 150 KV envelopes having as high as one-quarter of an inch thickness are employed. Some manufacturers have adopted a double-wall construction that, it is claimed, the total thickness of the two envelopes combined does not exceed that of a single envelope tube of the same rating. The practice, for these types of tubes, usually centers around the grinding of the portals to such thicknesses that x-ray absorption due to this portion is reduced to a minimum without sacrifice in the mechanical properties of the glass.

The gas pressure in an electron x-ray tube must be maintained very low so that the tendency for spontaneous ionization as a result of insufficient vacuum may be obviated. The trend is to exhaust these tubes to pressures between 0.01 to 0.0075 micron, while higher vacuum for high-tension sealed-off tubes becomes of essential requirement. It is only through the achievement of a sufficiently high vacuum that a complete control over the electron flow expressly by means of the temperature of the cathode filament can be insured.

Aside from eliminating all foreign gases and reducing the pressure of the tube to high vacuum, the problem of maintaining this vacuum by adequate choice of target material is of considerable significance. During operation of the x-ray tube, as the target temperature may rise to a value to cause the volatilization of the metal, and hence the rise in the vapor pressure, metals of high melting point and having low vapor pressure properties are used for target material. Tungsten, due to its extremely low vapor pressure and relatively high melting point, has proven to be an excellent target material.

As has been mentioned previously, the electrical energy (the current) for the production of x-rays must necessarily pass through the focal spot of the target. The magnitude of the permissible energy (rating of the tube) depends principally on the focus area, and, to a large extent, on the target material.

Since approximately 99% of the electrical energy passing through the focal spot is transformed into heat, the rating of an x-ray tube is determined by the instantaneous heat tolerance, the mechanical strength of the focus metal, and by the high heat conductivity of the anode incorporating the focal spot.

Copper has been selected as the anode material, and tungsten as that of the focus. The latter metal has the peculiar property of withstanding enormous mechanical stresses due to electron impact, and further possesses a high fusion point, low vapor pressure, fairly good heat conductivity, and, owing to its high atomic number (or, atomic weight!) it has favorable efficiency for the production of x-rays; whereas, copper has the inherent characteristic of high heat conductivity and relatively great mechanical strength.

The fusion point of pure tungsten is $3370^{\circ}\text{C}.$, while that of pure copper is $1083^{\circ}\text{C}.$ Copper has a thermal conductivity of approximately three times as high as that of tungsten. The combination, then, provides an efficient target material having high quality x-ray emission properties of tungsten together with excellent heat conductivity afforded by copper.

From a radiographic standpoint, the size of the focal spot, the thickness, and its angular position with respect to the field of exposure are of primary importance. The maximum *specific rating* (watts per square millimeter of focal area) of a tungsten focus of most favorable thickness of 1.7 mm adhering to the copper behind it is found to be 250 watts per second per square millimeter of focal spot area. Generally the focus metal has a thickness varying from 1 mm to 6 mm, depending on the type of x-ray tube.

In considering the load-carrying capacity of an x-ray tube, the shape and the angle of the focus play an important part. For instance, using a line-focus target of 20-degree angle, Fig. 38, substantially the same intensity of radiation as from a round-focus tube of 45-degree target angle is produced. A line focus is quadrangular, its length being several times greater than its width. It is further observed that a line focus can withstand loads twice as high as that carried by a round focus of identical target angle and optical effect. Thus, exposures as short as 50% of that with a round focus can be obtained with a line-focus type of x-ray tube.

The intensity of x-rays emerging from the target of an x-ray tube is dependent on the angle between the focal surface and the x-ray beam. X-rays whose emergent angles are large will give rise to a greater intensity radiation than that of those whose emergent angles do not exceed a few degrees with respect to the target surface. With zero degree angle, for instance, it is not possible to obtain the most useful x-rays, whereas with an emergent angle of only 5 degrees the radiation density of the x-rays is increased to approximately 85 per cent that at the most favorable angle, which is obtained at about 25 to 30 degrees. The phenomenon is fully illustrated in Fig. 43.

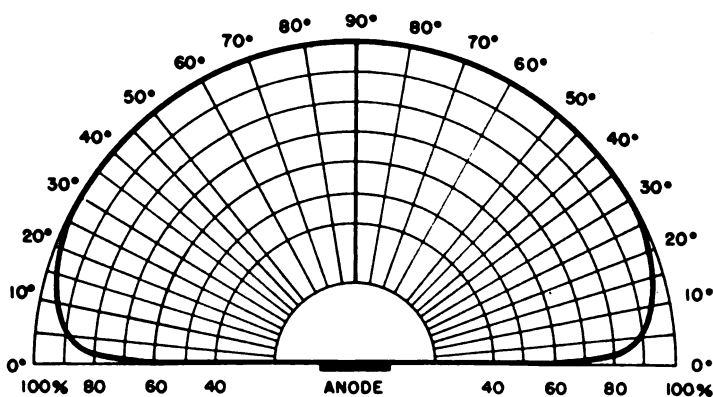


Fig. 43. Distribution of X-Ray Intensity As a Function of the Angle of Emergence.

A line focus has usually a target angle of 20 degrees with the vertical. At this angle the projected focal area is approximately 1/3rd that of the actual focus area. The x-ray intensity at the projected focus is then greater than that of the radiation emergent normally from the target face.

Owing to the projection of the focus with a 20-degree angle, an increase in radiographic detail is realized without sacrifice in speed. It should be kept in mind, however, that radiographs made at a short anode-film distance, for instance at 25" or less, will not receive a uniform radiation intensity especially if the area of exposure covers a relatively large field. This effect is due to those emergent rays that make an angle less than 5 degrees with the target surface, and therefore, possessing less radiation density,

with the result that blurring (or, at least a diminution in the sharpness of detail!) will occur at the anode side of the film. This fading off is known as the "*heel effect*," which becomes annoying at relatively short target-film distances. Because of the higher load capacity of the line focus tube compared with that of the round focus construction, the anode-film distance may be considerably increased without sacrifice in exposure time but with material improvement in radiographic detail. With a target-film distance of 30 inches or over, the "*heel effect*" entirely vanishes.

It will be noted that with a given line focus tube the maximum allowable film dimension is limited by the angle of the target face—the smaller this angle to a plane normal to the film the area that can be covered by the radiation is markedly reduced for a fixed target-film distance. A 14" x 17" film, which is generally used in routine industrial radiography, cannot be entirely covered with uniform intensity radiation without an increase in the target angle at a given distance, which, for a film of smaller dimension, may be the optimum position. Since an increase in focus angle will not be advisable, a more preferable recourse is to increase the tube-part distance and the impressed power, a considerable increase in which is permissible with a line-focus tube, and more particularly, where the tube is of *rotating-anode* type, which may carry 8 to 10 times the load of the *stationary-anode* tube having identical focal spot area.

4. Anode Cooling.—The electrical energy applied to the x-ray tube for the production of x-rays must necessarily pass through the focal spot. Nearly all of this energy is converted into heat, which is conducted through the copper anode shank to the exterior of the tube. Only a small fraction, 0.025% to about 1.0%, of the energy received at the target is effective in producing x-ray radiation. Recent reports, however, disclose that the development of an x-ray generator, producing 100,000,000-volt radiations equivalent to 1000 grams of radium, makes it possible to produce an x-ray intensity 10 times more powerful than gamma rays from radium. A 20,000,000-volt machine weighing four tons has been originally built at the University of Illinois. It is further claimed that the 100,000,000-volt machine, using powerful magnetic field, will also produce the first artificially-made cosmic rays.

It has already been stated that the *permissible load* of a diag-

nistic x-ray tube having stationary anode is a direct function of the focus area, and that the specific load capacity is approximately 250 watts per square millimeters of tungsten focus backed by copper anode. To illustrate this further, we have already observed that the most favorable type of focus which will conform to this requirement is the line focus with the principal ray (assumed x-ray beam projecting at right angles to the axis of the tube) at an angle of 20 degrees to the target face. At this angulation, a line-focus tube can withstand an impressed power nearly twice that afforded by a circular-focus tube (of 45° angle) having an equal effective focus area. In this discussion the actual focal spot size will not be considered as much of importance as the type of focus, its specific capacity, and the angular relation between the focus and the x-ray beam.

The relation of the specific capacity C_s has direct bearing on the radiographic quality of an x-ray tube, and may be given in an equation form as

$$C_s = \frac{W}{A} \quad (49)$$

in which, W is the total impressed power capacity of the focus in kilowatts, A is the effective focus area in square millimeters. But, the effective focus area A as projected from a line-focus tube is equal to the actual focal area on the target multiplied by the sine of the angle ($\sin \theta$) between the principal ray and the focal surface.

Assuming that the optimum specific capacity of a good diagnostic x-ray tube with stationary anode is 200 watts per second per square millimeter of the actual focal area, an arbitrary relation for the *quality* of an x-ray tube may be established in an expression given as

$$Q = \frac{C_s}{\sin \theta} = \frac{.2}{\sin \theta} \quad (50)$$

where Q is the arbitrarily chosen quality factor of the x-ray tube having a stationary anode.

Since, in a line-focus tube the principal ray projects perpendicularly to the long axis of the x-ray tube, making a 20° angle with the target face, the area of the effective focus will be about 1/3rd

that of the actual focus, i.e., the sine of 20° is 0.34. The *quality* of the tube may be given, then, as

$$Q = \frac{.2}{.34} = 0.6 \text{ approx.}$$

In the case of a circular focus of 45° angle, the effective focal area is 0.707 ($\sin \theta = 0.707$) times that of the actual focus. Hence, the quality of this tube may be expressed as

$$Q = \frac{.2}{.707} = 0.28$$

From the last expression, it is obvious that the load-carrying capacity of a round-focus x-ray tube is only one-half that of a line-focus tube.

Using the same analogy for illustrating the quality factor of a rotating-anode x-ray tube having a line-focus at an angle of 15° to the vertical, it can be shown that its optimum specific capacity is greater than that of a stationary-anode tube. That is,

$$Q = \frac{.2}{\sin 15^\circ}$$

$$= \frac{.2}{0.259} = 0.77$$

which latter quantity indicates that the optimum specific load capacity of a rotating-anode x-ray tube is approximately 250 watts per square millimeter ($200 \times 0.707/0.6 = 258$ watts).

From the above discussion it should become obvious that a stationary-anode diagnostic x-ray tube having a *quality factor* less than 0.5 should be discarded.

Since a greater part of the applied power is transformed into heat at the target, the temperature of the latter is determined by the specific heat and the thermal conductivity of both the tungsten focus and its copper backing, and further by the duration of the applied energy to the x-ray tube. With a given load on the tube, the rise in temperature of the anode depends upon the duration of the exposure time. Thus, unless a provision is made to conduct the heat from the tube, the target face may become so hot as to

volatilize, or even crack, with the result that the x-ray output of the tube will be considerably reduced, and continued operation may even cause the destruction of the tube.

Owing to the above factors arising from thermal considerations of the tube load, each x-ray tube is provided with an adequate cooling system. Some tubes are cooled by metallic radiators, while others are cooled by water constantly circulating behind the tungsten target backed by a few millimeters of copper. Still others are cooled by an insulating liquid, such as a purified mineral oil, which either completely surrounds the tube or circulates inside the anode by means of a special pumping unit, the rate of flow varying from 1 gallon to 15 gallons per minute.

One manufacturer* has devised a means for cooling the oil by tap water circulating at ground potential through corrugated copper coils in the tube head. The latter arrangement provides an efficient means of insulation between the tube bushing and the tube housing, and further offers the advantage of thermal conductivity of water which is approximately 8 times that of oil.

One other form of cooling is accomplished by the provision of a demountable spherical block of copper which has corrugated surface, blackened with a paint of carbon, to offer a large area of thermal convection. Some x-ray tubes, however, are cooled by air blown directly onto the tube or circulating under pressure behind the tungsten target. Such a blast of air is also used in cooling the demountable copper coolers.

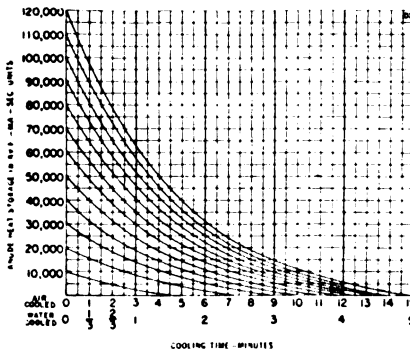


Fig. 44. Cooling Curves Applying to XP Coolidge X-Ray Tubes.

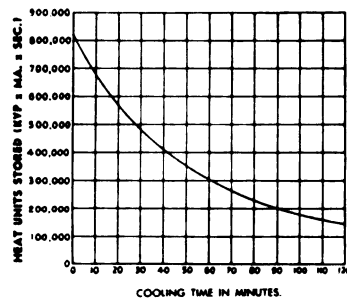


Fig. 45. Cooling Curves Applying to Eureka SP-3 X-Ray Tubes.

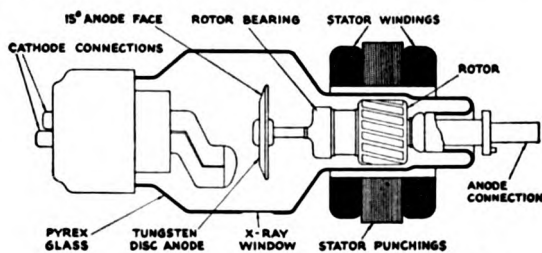
* Machlett Laboratories, Inc.

In making a series of radiographic exposures, it is not only important to know the maximum energy that can be safely used in individual exposures but also the frequency with which they can be repeated. To determine the minimum time interval necessary to cool the tube before the next exposure can be made, cooling curves have been carefully calculated for each particular type of tube by its manufacturer. These curves indicate the rate of heat dissipation from the anode of radiator-cooled or water-cooled (water contained in a reservoir attached at the anode end of the tube) x-ray tubes with various initial values of heat storage, which is expressed in arbitrary heat units, the product of the Kv.P. \times M.A. \times Seconds. Figs. 44 and 45 illustrate the different cooling curves for various x-ray tubes. These curves, however, do not apply to x-ray tubes having pump-circulated cooling systems, which usually maintain the target at normal operating temperatures for continuous use of the tube.

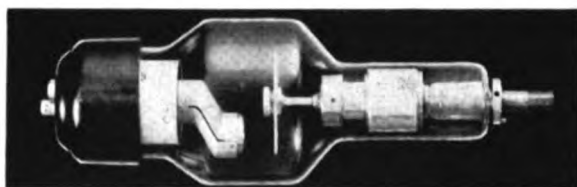
5. Rotating-Anode X-Ray Tubes.—The objective in radiography is one of producing sharpness of image with optimum definition of detail delineation. To accomplish this, the x-ray tube must have a small focus area and at the same time it must be capable of carrying large exposure loads. The attainment of this objective resides in the development of the rotating-anode x-ray tube. In the conventional stationary-anode tube the amount of electric energy which may be safely applied to the target is limited to a large extent by the focal spot area. In a rotating-anode tube, the anode is made to rotate at a high speed so that the cathode rays incident on the small focus remain stationary in space while the focal area under bombardment continuously changes, thereby cooler metal replacing the heated spot. Such an arrangement offers the advantage of permitting the use of a higher specific load on a very fine focal spot, thus producing a fundamental improvement in the radiographic quality.

Of the various rotating-anode tubes now commercially available is the one shown in Fig. 46. It is manufactured by the General Electric X-Ray Corporation. The tube has double foci, either of which may be used selectively. The tube permits the application of considerably larger loads than that afforded by a stationary-anode tube for the same exposure conditions, and hence the exposure periods are reduced to minimum values. The unit is

immersed in oil and sealed hermetically within a shock-proof and x-ray protective earthed container.



(a) The Diagram of the Rotating-Anode Tube.



(b) The Commercial Form of the Rotating-Anode Tube.

Fig. 46. The G-E Rotating-Anode X-Ray Tube.

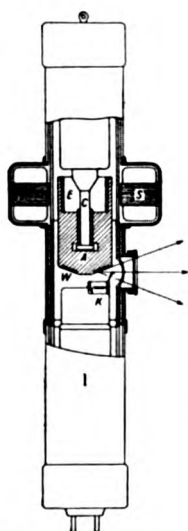


Fig. 47. The Philips Rotalix X-Ray Tube In Sectional View.

The Philips Metalix X-Ray Corporation manufactures an x-ray tube which comprises a conical tungsten target *W*, shown in Fig. 47, backed by a massive copper anode *A*, which is mounted on the spindle *C* having self-lubricating bearings. The anode is provided with a cylindrical extension to form the rotor of the A.C. induction motor constituted by the rotor itself in conjunction with a stator winding placed around the tube. An iron cylinder is snugly fitted inside the rotor to increase the magnetic flux threading the copper. *S* is the laminated iron core of the stator winding which is energized by a three-phase current source.

The cathode filament *K* is slightly off-centered in the direction of the tube window, allowing the cathode stream to fall on a trapezium-shaped focus area *F*. The focus track has a radius of 2.5 cms, and the breadth of the

focus varies from 1.2 mm to 2 mm. The speed of rotation of the anode varies from 20 to 40 revolutions per second, covering respectively a displacement of about *sixty* to *one hundred twenty* times the focus breadth. The tube is manufactured at load ratings of 20 KW to 200 KW-second.

Another rotating-anode tube deserving special commendation is available through Machlett Laboratories, Inc. The tube, commercially known as *Dynamex*, is shown in Fig. 48, in which (1) represents the silver lubricated bearings around which the all-tungsten anode disc (5) rotates attached to the spindle (3) form-

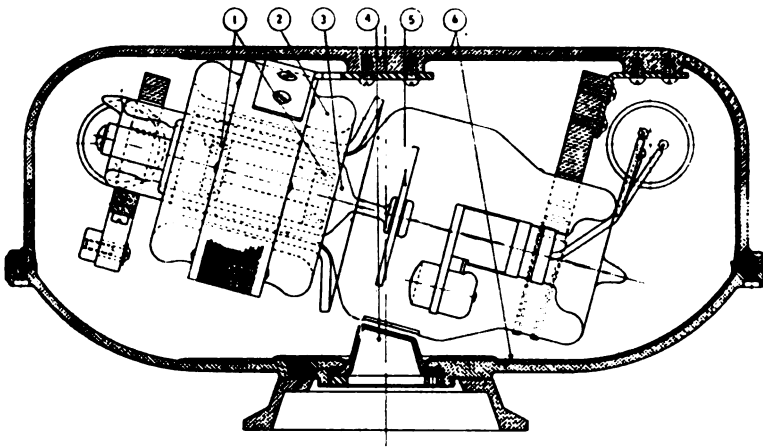


Fig. 48. Schematic Diagram of the Dynamex.

ing the rotor of the induction motor formed in conjunction with the stator (2). Like other rotating-anode x-ray tubes, the target of the *Dynamex* is mounted at 15-degree angle to the axis of the x-ray port (4). The unit has double foci, 1 mm and 2 mm square respectively (effective), and is sealed in a hermetic metal housing filled with insulating oil. The tube is designed to operate on either single-phase or three-phase current.

In the shock-proof enclosure of the *Dynamex* is built an automatic exposure counter which registers the number of times the tube is energized for exposure. The manufacturer further guarantees the tube to produce a minimum of 10,000 exposures during its useful life—a committal seldom resigned to become heralded by tube manufacturers.

Other outstanding characteristics peculiar to Machlett x-ray tubes are embodied in (1) the design of the cathode having a grid which serves to control the focal spot size and to some extent the quality of the radiation by biasing the tube by the application of an external potential; (2), the efficiency of oil-cooling system in which a minimum of 15 pints of oil per minute flows through the anode under a pressure of 40 pounds per square inch with an input temperature of 40°C.; and (3), since the viscosity and hence the stability of oil are directly influenced by high temperatures, an electrically controlled supply of water circulating at the rate of 1 gallon per minute through specially constructed cooling ducts serves to cool the oil, resulting in maximum available efficiency which meets the requirements of a diagnostic x-ray tube.

6. R-Output of X-Ray Tubes.—Every x-ray tube of manufacture is capable of generating a specific maximum of x-ray output, generally referred to as "*R-output*." This quality depends on the applied voltage and on the current through the tube as well as on the character of the target material. With an x-ray tube of high R-output it will be obvious that the effect will curtail a considerable reduction in exposure time with consequent improvement in the quality of the radiograph because of the favorable geometrical and electrical factors involved. Shorter exposure time thus accrued will further effect a diminution in physical strains on the x-ray apparatus, with the resultant prolongation in the life of the x-ray tube.

A comparative study of roentgen-output of different x-ray generating apparatus reveal that the variations in R-output are not altogether independent of the type of generating equipment, the wave-forms of the high tension current and the voltage, and the design and material of the tube envelope. Differences in the radiation output may also be found where x-ray equipments of different manufacture are compared, and where differences in the aerial system, rectification, type of valve and x-ray tube employed, and in the mains supply, are existent.

From observations of various investigators, and data obtained in the writer's laboratory, it has become quite obvious that the variations in the quantity and the quality of the x-ray output is intimately related to the generating equipment. The heating of the pyrex envelope during operation of the tube will, on some

machines, cause an increase in R-output, while in others, this will cause a converse reaction. When the glass envelope is cold (at a temperature below 212°F.) it retains its properties as a good insulator, and the stray charges collected on the inner surface of the glass produce a negative potential difference equal to the peak voltage of the cathode. During the falling of this voltage, the resident electrons on the glass wall, producing a grid action, effect a distorting influence on the electron stream, and may even totally prevent the electron emission from leaving the hot cathode. On the other hand, when the glass envelope is heated prior to the exposure it becomes conducting, and the charges flow freely through the glass to annihilate the field. This latter condition permits the tube current to flow to the anode not only at the peak value but also at the lower portion of the potential wave. Consequently, the R-output of the tube increases.

By far the most ideal solution to the problem of x-ray output is offered by the constant-potential generator. Since no modifications are involved in the wave-form of a constant-potential current, the radiation output is uniform regardless of the thermal condition of the tube envelope. To secure the best performance with this type of circuit, however, the ballast resistance should be kept at a minimum value in order that the condensers may sustain a constant normal potential.

For all practical purposes, the differences in R-output between half-wave tube rectified, four-valve rectified, or mechanically rectified circuits do not exceed several per cent. Quantitative variations in the output may arise, however, when tubes energized on different circuits, having different means of anode-cooling systems, are considered. On a voltage-doubling circuit, the difference of output by an air-cooled x-ray tube and that produced by a tube cooled by water-cooler is one-and-a-half times in favor of the latter type of generator.

In a comprehensive publication on the comparison of x-ray output as a function of the applied voltage, Taylor, Singer, and Stoneburner, in Bureau of Standards Journal of Research, Page 381, March, 1934, maintain that irrespective of the voltage wave-form the R-output per effective milliamperere for any given effective (root-mean-square) voltage remains same. That is, an x-ray tube impressed with any given effective voltage and operated on a

variety of voltage wave forms gives substantially the same R-output per effective milliamperere. There are, however, two most obvious factors involved as being responsible for the variation in R-output. One of these is the partial absorption of the radiation by the glass portal, and the other is in connection with the distortion of the voltage and current wave forms influenced by the x-ray tube itself and to some extent by the transformer reaction.

Variations in the radiation output due to various other causes are also existent, but with modern x-ray tubes of standardized design and material, and, to some extent, of circuits, comparative tests on tubes of identical load rating and anode construction indicate that the R-output still remains a function of the effective power applied to the target, and without disregard to the waveform of the electrical quantities. The effect is found to be further dependent, as has been mentioned on a previous occasion, on the atomic number of the radiator (target). For instance, when the element gold of atomic number 79 is used as a radiator, the R-output will increase 10 per cent over that of tungsten of atomic number 74, whereas the increase with thorium or uranium target will amount to 25 to 30 per cent. The principal objection against the use of these elements as target material is, in the case of gold, due to its low melting point, and for the latter two elements, the difficulty resides in their high vapor pressure when they are subjected to elevated temperatures.

7. Secondary Electrons.—In an x-ray tube, the electrons released from the cathode and moving at high velocities toward the anode are known as the *primary electrons*. The kinetic energy of these electrons is partially converted into x-ray radiation and partially into heat energy at the target as they impinge on it. Some of the primary electrons, however, after colliding with the focus metal bounce off from it and move at decreased velocities radially to the long axis of the tube and are finally attracted to the anode shank, or, to the glass envelope. These latter electrons are known as *secondary electrons*, or as *stray electrons*. Among these are included electrons which have been removed from the target metal by the primary electrons and are caused to diffuse back to the surface of the target metal. The effect, which may be termed, for convenience, "*the scattering of electrons*," principally forms the subject of the present discussion.

Whenever the rebounding secondary electrons from the target surface reach the glass envelope of the x-ray tube, they induce to the inner surface of the glass a negative electrostatic charge in respect to its outer surface, producing a difference of potential between the two surfaces. The kinetic energy $\frac{1}{2}mv^2$ of each electron may appear, in the glass, as heat energy $Ve/300$. Consequently, a small amount of gas may be liberated from the glass walls of the tube. The gas, if ionized, will permit the passage of some of the ions from the electrodes, through the glass, to the air, and back to the respective electrodes, producing electrolysis of the heated glass, and possibly, a destructive discharge.

Some of the rebounding electrons, however, may become attracted back to the anode shank and hit it all over its surface with decreased velocities, giving rise to *stem radiations* (whose intensity is approximately 200 times weaker than the direct radiation) possessing relatively long wavelengths. Or, these electrons may produce tertiary electrons, which, in turn, may give rise to tertiary x-rays, and photoelectrons, or even to Compton electrons (recoil electrons). This results in an impairment of the uniformity of the useful x-ray beam reaching the film, since the radiation, instead of proceeding only from the focal point, will be projected from a comparatively larger area in the tube. The condition will inevitably cause blurring or unsharpness in the radiograph.

To do away with the deleterious effects of the stem radiation incited by the stray electrons, a tube design offered by the General Electric Company surmounts these difficulties. The important feature of the tube resides in the provision, around the anode, of a cylindrical copper shield which intercepts the escaping secondary electrons from the target face. Two apertures are provided in this shield—one, for permitting the passage of the cathode stream to the anode, and the other, for the primary x-rays proceeding from the focal spot toward the film. A schematic diagram of the sectional view of the tube illustrating the positions of the cathode and the cylindrical shield in respect to the anode is shown in Fig. 49.

As the electrons projected from the cathode filament F pass through the cylinder C immediately surrounding the anode and strike the tungsten target T , the kinetic energy of some of the

electrons becomes converted into heat at the target, whereas that of others produces x-rays. Some of the electrons in the cathode bundle may rebound from the surface of the target with lower velocities. Because of the relatively small heights of the trajectories of these

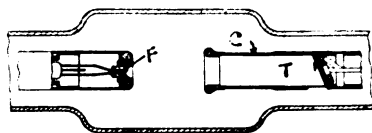


Fig. 49. The Electron-Shielding Cylinder Surrounding the Anode of the G-E High-Voltage X-Ray Tube.

stray electrons, the latter are unable to get out of the cylinder, but are attracted to it and carried away through the circuit. The arrangement, thus, eliminates possible electrostatic stresses otherwise likely to occur in the glass

envelope due to an accumulation of secondary electrons thereupon.

In an article on "Secondary Electrons In An X-Ray Tube," *Physica*, Vol. 12, Page 274, 1932, Bouwers and Tuuk describe various designs for cathode and anode structures, pointing out that no screening device for the secondary electrons is necessary if sufficiently large area is given the anode face surrounding the focal spot. It is further shown that the fastest secondary electron leaves the target surface at 45° angle, with a maximum range of twice the distance between the cathode and the anode. Thus, the minimum interelectrode space must not fall short of the height of the electron trajectory, which is $\frac{1}{4}$ th the entire range of the electron. To restrict the rebounding electrons to the front face

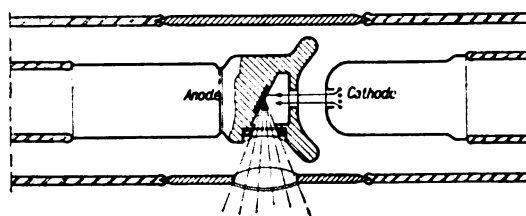


Fig. 50. Schematic Illustration of the Principle of Restricted Range.

of the anode, then, the diameter of the anode and that of the cathode is made at least four times the interelectrode distance.

The authors further describe an example embodying the *principle of restricted range* in which the electrodes assume spherical configurations, shown in Fig. 50. Because of the gradual curva-

ture of the cathode, and of the anode cap, there exists no edges having pronounced curvatures that would likely give rise to cold discharges in view of high field density due to the application of high voltages.

In another pertinent article appearing in "Zts. Techn. Phys., Vol. 18, Page 209, 1937," Bouwers and Kuntke present a further

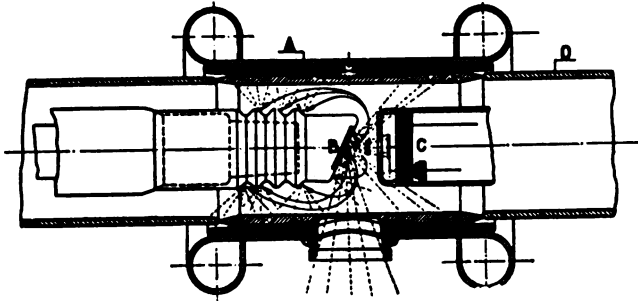


Fig. 51. Metalix Metal-Centered High-Voltage X-Ray Tube.

method of restricting the effect due to stray electrons to the interior of the x-ray tube by constructing the center part of the tube envelope of chromium-iron surrounded with a layer of lead at ground potential. The electrons rebounding from the target surface hit the anode again all over its surface, producing stray x-radiations. But, as will be obvious by a glance at Fig. 51, most of the stray electrons will be conducted to earth by means of the earthed metal chamber, and the effect of those which will give rise to stray x-radiations is confined to the interior of the metal-centered x-ray tube.

CHAPTER V

X-RAY RADIATIONS

1. **Discovery of X-Rays.**—No account of any branch of pure science will be complete without a brief reference to the romance of its beginning, development, and pursuant trends arising from its attributes of consequence. Of such significantly economic importance to present day has been the discovery, and subsequent use and application, of x-rays in diverse phases of industry as well as in medical practice, and hence, securing the safety and comfort of mankind that the reviewing of the several aspects of the background foreshadowing the advent of the field of industrial radiography can hardly be overlooked in this present writing.

November 8, 1895, depicts one of the most fortuitous achievements in all science of the nineteenth century. On that day, Wilhelm Konrad Roentgen, professor of physics at the University of Wurzburg, while studying the nature of electric discharges through rarefied gases, discovered the new radiation, which he called "*X-Rays*" because of its peculiar nature unknown to him at the time. Roentgen hardly realized then that the newly-discovered radiation was destined to play an important role in revealing the hidden structures not only in human beings but in materials of industry. That the radiation would be used in combating malignant diseases, and detecting flaws in metals and thus preventing failure frequently encountered with defective parts in service. Such utility, indeed, need be considered as one deserving great esteem in the scientific world.

Roentgen's experiments comprised the study of radiations from a highly evacuated pear-shaped glass bulb with a sealed-in electrode at each of the two opposite ends of the bulb and connected to the terminals of a high-voltage induction coil. The apparatus was set up in a darkened room where visible light of any character even from that of his discharge tube, which was enclosed in a closely-fitted black paper, was excluded. But, quite accidentally, Roentgen observed a faint greenish illumination on a square piece of cardboard impregnated with Barium Platinocya-

nide and lying on the table near the apparatus. The fluorescence of the cardboard screen was equally effective whether its treated or the back surface was held toward the tube, and that the phenomenon was distinctly observable on the screen even when it was held within a radius of several yards from the discharge tube.

The new radiation could traverse paper, wood, cardboard, mica, glass, amber, and other opaque objects with great ease. A large volume of book interposed between the tube and the fluorescent screen had no effect on the fluorescence of the screen. But, metals such as aluminum, copper, tin, zinc, silver, and gold were less amenable to the rays.

It was while picking the cardboard fluorescent screen that his fingers became interposed between the tube and the screen and Roentgen observed the bones of his fingers delineated on the treated surface, as the flesh of the hand was more transparent than the bones. Further observations of the effect of the radiation proved that the emulsion of a photographic plate wrapped in black paper and held against the emanation from the tube became black upon development.

Roentgen was soon convinced that when the fast-moving cathode rays from the cathode in his tube became incident upon any part of his discharge tube they produced a radiation of entirely different character from that of the cathode rays inciting it. Not knowing the exact nature of the new radiation, Roentgen called it "*X-Rays*." The emission was more prominent from the anode, which was of a straight metal wire, than any other part of the tube, and that anode metals of greater density produced more intense radiations.

Thus realizing the possibilities of these x-rays and their applicability to photographing the internal structures of different materials, Roentgen subsequently devoted most of his experimental efforts to "*x-ray photography*." Among the x-ray "*pictures*" that he made of many objects are a pocket compass, a door-knob, a key, his shot-gun, and an image of his hand. Thus has been the beginning of a new type of utility which has already proven a valuable tool not only to the medical profession but to diverse industrial applications.

2. Characteristics of X-Rays.—Preceding Roentgen's discovery, early experimenters had already observed that the cathode

rays exhibited a peculiar penetrating power through matter intercepting their path of progression, and that photographs (shadow pictures) of objects traversed by these rays could be made on the photographic plate. They failed, however, to make the application suggested later by Roentgen who made use of the radiation emanating from the anti-cathode (*x-rays*) instead of that from the cathode (*cathode rays*). The significant point of Roentgen's application becomes readily obvious in that the cathode rays consist of negatively charged particles of electricity of definite magnitude of mass and having an effective penetrating power to a depth of only a few millimeters in contrast with x-rays which are transverse electromagnetic vibrations bearing striking similarities in many respects to visible light; and, owing to their extremely short wavelengths, x-rays can penetrate matter to a depth of one foot or over, depending on the density and the character of the material traversed.

Some of the similarities between the x-radiation and light are exhibited in the phenomenon of their identical velocity of propagation through space in straight lines, in their affecting a photographic plate, producing fluorescence or phosphorescence in certain chemicals, in their property of diffraction and polarization, and in their power of ionizing gases to variable degrees. It has been lately proved that x-rays, like light rays, can be deflected, reflected, and refracted under specific and controlled conditions.

The prediction by Laue, in 1912, that x-rays possess the peculiar property of becoming diffracted by crystals as light from an optical grating has fully established, by experimental confirmation, the essential similarity of x-rays to light rays—a distinguishing difference between the two waves being one of wide spectral range possessed by x-rays and their having considerably shorter wavelengths than those of light. As predicted by the classical theory, x-rays, or, light waves, in general, consist of a train of oscillatory motion originating from a source point by the mutually perpendicular linkage of electric and magnetic waves at right angles to the direction of travel. Such a phenomenon, indeed, occurs as continuous progression of the radiation waves in straight lines. The energy of the radiation may be resolved into discontinuous and rapid successions of *ether disturbances* taking corpuscular forms better known as *quanta* or *photons*, unit energy

particles of light, defined by the values of hf , where h is Planck's constant equal to 6.55×10^{-27} *erg-second*, and f is the frequency of the photon. It then becomes evident that the greater the frequency of the radiation the shorter the wavelength, and hence the greater the penetration power of the photon as given by equations (27) and (28), which may be written as

$$\lambda = \frac{hc}{Ve} \quad (51)$$

and,
$$f = \frac{Ve}{h} \quad (52)$$

where, λ is the wavelength of the photon, f its frequency, C is the speed of light equal to 3×10^{10} cms per second, V is the applied voltage to the tube, and e is the charge of the electron in e.s.u.

The penetrativeness of x-rays is a function of the character of the substance traversed. The greater the thickness of a given material the more opacity it offers to the penetration by x-rays. This penetrative property of x-rays also depends on the density and on the atomic number (or, atomic weight) of the substance, the greater the values of these properties the less the penetration. Since x-rays are differentially absorbed by matter, the extent of their penetrativeness will be limited by the greater density and higher atomic number of heavy elements. Metals such as aluminum, and magnesium, and thin sheets of copper, tin, zinc, and most organic substances such as wood, fiber, cardboard, bakelite, lucite, and other plastic materials are readily traversed by x-rays of ordinary wavelengths.

Since a radiograph is shadow representation, on the photographic film, of a part exposed to x-rays, the blackness or the density of the image will depend on the penetrativeness of the radiation, which latter quality, in turn, varies with different densities, or different thicknesses in the case of metals, constituting the material radiographed. X-rays of ordinary penetration quality, such as employed in radiographic work, may fully penetrate one group of materials yet they may fail to penetrate, to the same extent, others which may possess comparatively high densities, or greater thicknesses, and other physical characteristics which make them

less amenable to x-rays than the former group. Hence, the *quality* (penetrativeness) of the x-rays must be varied to compensate for this variation.

In considering the penetrability of a given material by x-rays, it is, indeed, a true fact that the sound portions of the given object or part is penetrated relatively to a smaller extent than that having gross defects such as *blow-holes*, *shrinkage pipes*, or *inclusions* of extraneous materials of lower density than the object itself. Thus, these imperfections cause irregularities in the densities of the various portions of the material, making the defective regions more amenable to x-rays in contrast with the sound material when radiographed on a film. This renders the observation of a defective part more pronounced by the formation of a peculiar shadow gradation in the image. Such an application finds wide use in the detection of inhomogeneity in metals and the presence of uncertain gross structures, especially in castings, without destroying the part under inspection.

Non-metallic inclusions, *gas cavities*, *micro-* and *macro-shrinkage cavities*, and *cracks* are characterized by darker shadows in contrast with the surrounding sound material. Metal *segregations*, usually of a greater density than the base material, are less penetrable and therefore exhibit lighter delineations or areas. It should then be apparent that x-ray inspection of forgings, machined parts, extrusions, and castings to insure soundness is not only inexpensive in the long run but also forms an authentic index to the designing engineer or to the founder in his effort to produce technically sound material by improving his method of designing, molding, and processing.

The general character of x-rays may be better understood by considering the radiation as being analogous with the phenomenon of sound waves produced by the impact of bullets on a sound-producing target, the bullets representing the cathode rays, and the sound waves the resulting x-rays. The principal difference between the two is one of wave-carrying medium, viz., the propagation of sound is a *molecular* disturbance while that of x-radiation is *spatial* or *ethereal* (the latter term being used for sake of convenience, and for lack of an appropriate term which might have been more explanatory).

Some of the principal characteristics of x-rays with which

the scope of this text is concerned may be summarized as:

- (1) X-rays are invisible transverse electromagnetic vibrations propagating from the anode of an x-ray tube in straight lines.
- (2) X-rays have wavelengths ranging from 0.004 to 1100 angströms.
- (3) X-rays propagate with a velocity of approximately 3×10^{10} centimeters per second (186,000 miles per second), as does visible light.
- (4) X-rays cannot be focused to a point.
- (5) X-rays ionize the gas which they traverse.
- (6) X-rays are capable of photographically affecting the sensitive emulsion of a photographic or radiographic film.
- (7) When x-rays are incident on matter, they produce secondary x-radiations, and photoelectrons.

3. Production of X-Rays.—It has been already observed that when a stream of fast-moving cathode rays are suddenly stopped by the target of the x-ray tube, an emission of radiation entirely different in character from that of the cathode rays occurs from the focal area. This radiation, already referred to as "*x-rays*," traverses through space with the speed of light, and penetrates almost any object intercepting its path. It will be again pointed out that x-rays in many respects are identical in character with visible light, one principal difference residing in the wide range of spectral distributions and of extremely short wavelengths possessed by x-rays compared with those of the visible spectrum.

In an x-ray tube, as the cathode rays become incident upon the target surface of the anode (which consists of a block of metal such as tungsten, nickel, copper, platinum, iron, or thorium) they penetrate a few microns into its interior, where most of the energy of the cathode rays is transformed into heat radiation, only a small percentage, between 0.01 to 1.0 per cent, inciting the atoms in the target metal to x-ray emission. The intensity of this issue depends upon the applied voltage to the tube, the character and the thickness of the target material, and on the quantity of cathode rays and their speed effecting the incitation of the target material to x-radiation. With certain limitations, the variation of the emission is a function of the

square of the applied voltage. Target materials having higher atomic number, and hence of greater atomic weight, will produce x-rays of greater penetrating quality than those emitted by the lighter substances under identical voltage and current ranges. The impressed voltage further affects the magnitude of the wavelengths and hence the penetration power of the x-radiations.

Practically all the electrons in the bundle of the cathode stream leaving the thermionic cathode will possess the same kinetic energy determined by the potential difference across the x-ray tube. This kinetic energy is transformed in the target partially into heat and partially into x-rays. The output of the latter radiation consists of a heterogeneous mixture of wavelengths, the corresponding radiation frequencies varying inversely as the wavelengths. This variation in the magnitude of the wavelengths is due to the differential absorption of the cathode ray energy by the various atoms of the target material and their subsequent excitation in accordance with the energy received by the electrons inciting the radiation. The effective wavelengths, however, vary inversely as the impressed voltage.

From the foregoing discussion it is now apparent that the production of x-rays by the impact of the cathode rays on the target of the x-ray tube is the converse phenomenon of that of photoelectron emission. The latter effect occurs when a beam of light quanta (energy particles of light) possessing energies dependent on the frequencies of the individual photons become incident upon the sensitive surface of the phototube emitter (a metal such as cesium, sodium, etc., or a compound such as cuprous oxide, forming the cathode of the tube) and eject electrons with kinetic energies ranging from zero to a maximum. While the intensity of the photoelectric emission is a direct function of the quality and of the quantity of the incident radiation and of the nature of the emissive surface, the kinetic energy of the photoelectrons remains independent of the intensity of this incident beam. In other words, the number of photoelectrons escaping from the emitting surface of the phototube will increase as the intensity of the incident radiation is increased. The average kinetic energy with which the photoelectrons will leave the surface, however, is dependent on the wavelength, or the frequency, of the light quantum causing this emission. The

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latter relation may be expressed by Einstein's photoelectric equation, which gives

$$\frac{1}{2}mv^2 = hf - \emptyset \quad (53)$$

$$\text{or,} \quad \frac{1}{2}mv^2 = \frac{hC}{\lambda} - \emptyset \quad (54)$$

in which, f is the frequency and λ the wavelength of the incident light ray with velocity C ; \emptyset is the work function or the energy required to just remove a photoelectron to the surface of the emitter, and m is the mass and v the velocity of the escaping photoelectron.

An effective method of increasing the photoelectric current is to partially fill the phototube with an easily ionizable gas such as neon, argon, krypton, xenon, or mercury vapor. Owing to the fact that the primary electrons liberated from the activated cathode will suffer a number of collisions per centimeter path, some of the gaseous atoms will undergo ionization. The newly formed negative ions (electrons) accelerating toward the anode will produce other electrons from the atoms with which they collide. The process, known as *cumulative ionization*, will proceed in geometrical progression, and may be given in an equation form as

$$N = N_0 e^{ax} \quad (55)$$

in which, N_0 is the initial number of photoelectrons leaving the emissive surface, N the total number of electrons reaching the anode (including cumulatively ionized electrons), e is the base of Napierian logarithms, a the coefficient of ionization (electrons produced per centimeter path), and x is the distance between the cathode and the anode.

Since the photoelectric current I_0 due to photoelectrons leaving the treated cathode surface is proportional to the number of primary photoelectrons N_0 , and the tube current I is proportional to the number of electrons N arriving at the anode, the equation (55) may be expressed in terms of the initial photoelectric current I_0 and the saturation current I . Thus, we may equate.

$$I = I_0 e^{ax} \quad (56)$$

where, I_0 is the initial current at the cathode, and I is the total photoelectric current flowing through the circuit. The relation will apply to any gas-filled discharge tube under controlled electrical conditions.

We may express the production of x-rays, therefore, by the relation of energy transformation by representing the converse of the photoelectric process; and, assuming that all the voltage energy $Vc/300$ on a given cathode particle appears as kinetic energy immediately preceding its collision with the target, and further assuming that this entire energy has resulted in the production of a corresponding x-ray photon from the target, we may write

$$\frac{Vc}{300} = \frac{1}{2}mv^2 = hf \quad (57)$$

or, simply,
$$\frac{Vc}{300} = hf \quad (58)$$

and, substituting C/λ for f from equation (52), we obtain

$$\frac{Vc}{300} = \frac{hC}{\lambda} \quad (59)$$

in which, V is the applied voltage in volts, and e is the charge of the electron equal to 4.802×10^{-10} electrostatic unit.

From which latter equation, solving for the wavelength, we obtain

$$\lambda = \frac{300hC}{Ve} \quad (60)$$

It will be noted that the work function ϕ as given in the photoelectric equation is neglected, owing to the fact that in the production of x-rays ϕ stands for x-ray emission work function, which is extremely small with respect to thousands of volts employed in the acceleration of the cathode rays.

From equation (58), it becomes obvious that the energy of the x-ray photon hf varies directly as the impressed voltage on the x-ray tube. Furthermore, since this photonic energy is directly associated with its penetrating power, our previous

inference that the latter quality is dependent on the voltage applied to the tube is thus confirmed.

To elucidate our discussion, let us refer to Fig. 52, which represents, for instance, an atom of a target metal of high atomic weight, and, for sake of convenience, the extranuclear electrons are excluded from the orbital field. In the normal state of this atom (i.e., when it is neutral) all the extranuclear electrons are in motion in their *stationary states* or *orbits*. These stationary states are characterized, proceeding along the sequence of orbits

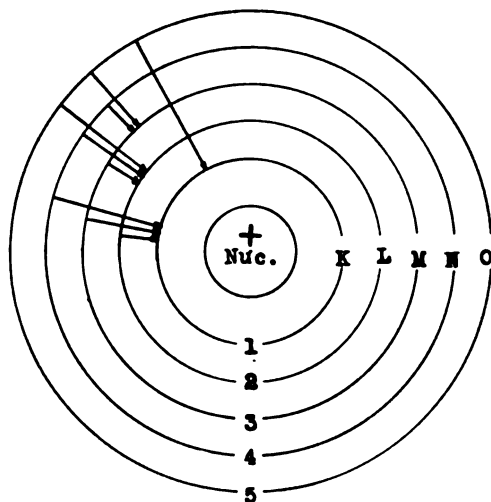


Fig. 52. Illustrating the Electron Radiation from Various Energy Levels of a Heavy Atom.

from the nucleus outward, by quantum number 1, quantum number 2, quantum number 3, and so on, to the outermost orbit. These orbits are also known respectively as *K*-, *L*-, *M*-, *N*-, *O*-, etc., energy levels. That is, the *K-level* is an orbit of quantum number 1, the *L-level* is one of quantum number 2, etc., as illustrated in the figure. Hence when an electron is in orbital motion normally, say, in the 2nd or *L-orbit*, then it is said to be occupying the level of quantum number 2; and, when an electron occurs in the 3rd, or *M*-, orbit, it is then known as an electron of quantum number 3, and so on.

If the atom shown in Fig. 52 is bombarded with an electron

of sufficient energy to remove an electron, for instance, from the *K-level* to, for instance, *M-level*, the electron of transition is now said to be revolving in an orbit of higher quantum state than the normal, thus increasing the energy of the new orbit, or the *M-orbit*, with a corresponding decrease in the energy of the first orbit. The atom, then, is said to have been transferred to an excited state, and the process in which the electron is removed from a normal to one of higher quantum state is known as *excitation of the atom*, which requires energy (supplied by the colliding electron). But, an atom having an excess of an electron in a given orbit (the *M-orbit* in our discussion) than that orbit can normally retain is in an unstable state. Therefore, the electron normally returns to its original orbit (the *K-orbit*). The transition from a level of higher quantum energy to one of lower energy state causes the electron to *radiate*, giving rise to a *quantum of light*, called a *photon*, of energy equal to the difference of energies between the two orbits.

Similarly, an electron making a transition, for instance, from *O-level* to *K-level*, the radiation energy will be given likewise by the difference of energies between the *O-level* and the *K-level*. If the photonic energies are compared, the photon produced by the electron transition from the *O-level* to the *K-level* will possess greater energy (shorter wavelength) than that produced between the levels *M* and *K*, since it will take greater energy to remove an electron to the *O-level* than to displace it to the *M-level*, owing to the fact that the electron or electrons in the inner orbits of the atom are under a greater influence of the nuclear electrostatic action than those in the outer orbits. Because the energy received by the *transition electron* must be expended in producing a radiation energy, the two energies must be equal. Hence, an electron radiates with the same energy with which it has occurred in a higher stationary state.

By the same analogy, an electron falling from an *O-orbit* to, for instance, *L-orbit* will possess higher radiation energy (shorter wavelength, and higher frequency) than that making a transition from the *N-orbit* to the *L-orbit*. Similarly, radiations incited from *M-*, *N-*, or *O-level* will respectively possess less and less energy of radiation and longer wavelengths, with the result that x-rays emitted from the innermost orbit of a

heavy atom will be more penetrating than those occurring from the outer orbits.

According to *Ether-Pulse Theory*, the high velocity electrons as they collide with the target of the x-ray tube, some of the orbital electrons will experience an acceleration radially to the atom. In an acceleration of this type, the electron *must radiate*, as depicted by the electromagnetic theory. The emission embodies a succession of pulses, frequently known as "*ether pulses*," which could be resolved into wave-trains of heterogeneous wavelengths, depending on the impressed voltage and on what electrons are excited to emission. All materials are relatively more transparent to the shorter wavelength radiations than to those of longer wavelengths.

But, transcending the above theory is the one offered by the *quantum mechanics* which imputes the penetrating quality of an x-ray radiation with the frequency conserved in the photon as emitted from the target. It is already noted that this quality depends upon the impressed voltage, and upon the target metal. The higher the voltage, and the higher the atomic weight of the target material the shorter the wavelengths and higher the frequencies of the resulting x-rays, and hence the quality of the x-rays thus produced will be *hard*. X-rays with longer wavelengths and lower frequencies are readily absorbed by matter, and therefore, they are described as *soft x-rays*.

4. X-Ray Wavelength Ranges and Their Use.—It has already been noted that the penetrating quality of x-rays is dependent on the voltage applied to the tube. The greater the impressed voltage the more penetrating are the x-rays thus emitted. X-rays produced at relatively low voltages, such as 5 to 25 kilovolts, are referred to as *soft x-rays*, since they will be readily absorbed by matter; and, those produced at tensions from 25 to 100 kilovolts may be called x-rays of *medium* penetration. From 100 kilovolts to several million volts will produce x-rays of more penetrating character, and the radiation of this penetrating power frequently is referred to as *hard x-rays*.

Since the penetration quality of x-rays depends on the applied voltage, and which affects the wavelengths of the radiation directly, we may express the relation in a convenient equation form as

$$\lambda = \frac{12345^*}{V} \quad (61)$$

where, V is the applied potential in volts, and λ is the wavelength in angstroms. The equation is derived from formula (60) by substituting the numerical values of the various constant quantities and solving for the wavelength in terms of the voltage value.

In industrial radiography, the penetration power of x-rays from a given x-ray tube is expressed in terms of the operating voltage of the generating apparatus. This is preferred to expressing the quality of the x-rays in angstroms, since the exposure techniques are expressed in kilovolts, and one does not have to stop and make conversions from one expression (kilovolts) to another (wavelength in angstroms). However, we shall classify different exposure techniques for different materials according to the kilovoltage employed.

An x-ray generator having one of the lowest tension ratings is the microradiographic apparatus whose operating range is 4000 to 8000 volts. In an alternative range, a beam of characteristic radiation incited by voltages such as used in a diffraction unit is employed especially in multiple radiographic work. In either case, the microradiographic procedure consists of making a thin section (about 0.005" thick) of the metal under examination and polishing it with No. 000 abrasive lubricated with a 50-50 mixture of oil and kerosene. The specimen is then placed in contact with a Lipmann emulsion film or an equivalent grade of fine grain film. A 5" x 7" sheet of lead of $\frac{1}{8}$ " thickness and having a hole approximately 1 mm in diameter drilled at its center is placed over the specimen and radiographed from above. The resulting black dot on the film (after it is developed) is magnified several hundred times under a microscope or is projected on a screen to reveal any inhomogeneous structure, discontinuity, or to some extent the residual stresses internal to the metal.

Since differential absorption is essential in the successful interpretation of the specimen structure under investigation, careful consideration should be exercised in selecting the proper thickness for a given specimen. Materials having high density require

* The exact value of this quantity is 12354, but 12345 is chosen because of convenience in remembering the formula.

thinner mounts than those of low density such as aluminum, magnesium, and their alloys. Hence, the exponential law of absorption, $I = I_0 e^{-\mu x}$, as given in equation (64), will apply invariably. The scheme has been successfully used with ferrous and nonferrous specimens, with wood, plastic, crystals, and with biological specimens.

Lately, radiography has also occupied a prominent realm in the field of art. Radiographs of flowers of various species have been successfully produced with highly decorative results. Examination of paintings to determine whether the work is genuine or an imitation has lent the use of x-rays to great service in this line. All old paintings, (which are done with inorganic pigments in contrast with organic dyes used in modern paintings) when retouched, can be readily detected and imitation work can be discriminated from that of true masterpiece. In this category of work, the x-ray tube voltage ranges from 10 to 18 kilovolts for radiography and up to 25 kilovolts for fluoroscopy. Such a range may also be used for plastic and fruit industries.

Study of fine structures of materials comprising pure metals of very low density, alloys, structures of annealed and heat-treated metals, paints, pigments, ceramics, plastics, textiles, and crystals of various compounds may be accomplished by x-ray diffraction patterns. The exposure technique consists of high milliamperage (20 to 1000 milliamperes), low kilovoltage (25 to 60 kilovolts), and relatively long exposure times. Constant potential and full-wave rectified currents are preferred in this type of work, though other types of rectified currents are also used. High intensity monochromatic x-radiation is desirable for uniform and consistent analytical results. A continuously pumped x-ray tube with interchangeable target is, indeed, of great advantage. Copper, cobalt, iron, tungsten, and molybdenum are some of the metals that may be employed as target material.

For examination (diffraction method) of iron and steel, a cobalt target is recommended, whereas copper is suitable for most any substance. For experiments requiring continuous spectrum, a molybdenum or a tungsten target is preferable. The former has the added advantage in that the tube may also be used as monochromatic x-ray generator. When it is desired to obtain practically homogeneous radiation, a zirconium filter may be

used with a molybdenum target, nickel filter with copper target, and manganese filter with iron target. A typical Philips Metalix water-cooled research tube is shown in Fig. 53.



Fig. 53. Philips Metalix Research Tube.

Metal parts, such as aluminum, magnesium, copper, bronze, steel, etc., may be examined by an x-ray machine having a rating of 85 to 90 kilovolts. Gross defects or discontinuities amounting to a few per cent (2%, U. S. Army requirements) of the total thickness of the material can be readily detected. An apparatus of this range having a continuous rating can handle magnesium or its alloys up to 3 inches thick equivalent to 2 inches of aluminum, $\frac{1}{2}$ inch of steel, and $\frac{2}{5}$ inch of copper or bronze. The above figures, however, are further dependent on the milliamperage range, the roentgen output of the x-ray tube, the focus-film distance, and on the duration of the exposure.

Steel forgings or castings up to a maximum of $1\frac{1}{2}$ inches thick, copper equivalent to 1.2 inches, aluminum equivalent to 4.5 inches, and magnesium equivalent to 6.5 inches may be examined with an industrial unit of 150-KV capacity at long (about 8-10 minutes) exposure durations and at usual focus-film distances.

Using a relatively high milliamperage, between 20 to 25 milliamperes, a continuously cooled x-ray tube of 220-KV rating can radiograph steel up to $3\frac{1}{2}$ inches thick, and copper or bronze to $2\frac{1}{3}$ inches, at the usual focus-film distance. This voltage on magnesium and aluminum castings of great thicknesses may be used to advantage to some extent. The equivalent thicknesses for these metals are found in Table VIII, Chapter VI.

Materials of gross structure ranging from steel $5\frac{1}{2}$ inches thick to copper 5 inches thick may be radiographed with an equipment of 400-KV capacity. This voltage may also be employed for the examination of concrete structures up to 8 inches to 1 foot in thickness. It should be noted that the use of a

voltage of this magnitude for the examination of thick parts of aluminum and magnesium should not be encouraged, as the radiation at this tension is so penetrating that the latter metals will be too transparent to produce proper gradation of radiographic density and to present sufficient degree of detail delineation to be of any diagnostic value.

There are on the market various x-ray units operating on voltages of 600 kilovolts to 800 kilovolts, and are used to radiograph heavy metals up to 7 inches thick. But, the most outstanding of the high-voltage apparatus of the latter order is the one-million-volt x-ray generator, by which steel up to 9 inches thick can be radiographed at a target-film distance of 32 inches in surprisingly short exposure durations. Owing to its variable focus area—0.6 mm to 3.0 mm effective—the radiographs made by this x-ray tube possess high magnitude of detail sharpness. The radiographic sensitivity of the unit is $\frac{1}{8}$ inch per 6-inch thickness, and $\frac{5}{32}$ inch per 8- to 9-inch thickness of steel, other metals being considered in relation to equivalent thicknesses.

5. Absorption of X-Rays.—In making an exposure, the useful x-ray energy reaching the film for producing the proper blackening, and hence the image, is the difference of the quantity of the primary emission from the x-ray tube target and that absorbed or materially transformed by the medium between the target and the film. This medium, in our discussion, is the metal object itself, which offers a certain amount of opacity to the transmission of the radiation.

Mention was made in the foregoing discussion that the relative opacity of different substances to x-rays is dependent on the density, thickness, and on the atomic weight (more particularly on the atomic number) of the material placed in the path of the radiation beam. It should be further noted that the softer the radiation (having long wavelengths) the easier it is absorbed by matter; and, conversely, the harder the rays (having short wavelengths) the more penetrating they are and are absorbed only to a smaller degree. Hence, *the absorption of x-rays is a function of the density, thickness, and atomic number of the material*, and further varies with the quality (magnitude of wavelengths) of the radiation leaving the x-ray tube target (the primary radiation).

X-rays, in traversing matter, are absorbed by it differentially. If the primary beam leaving the focal spot has an intensity, for instance, I_0 , as it traverses an object placed in its path a diminution in its intensity occurs. The emergent x-ray beam of intensity, for instance, designated by I , may be calculated by a reference to Fig. 54.

If the magnitude of the diminution of x-rays per centimeter path in traversing the slab of thickness X is designated by μ , then the extent of decrease in the intensity of the beam in traversing the increment dx will be $\mu \cdot dx$. The intensity I_0 will

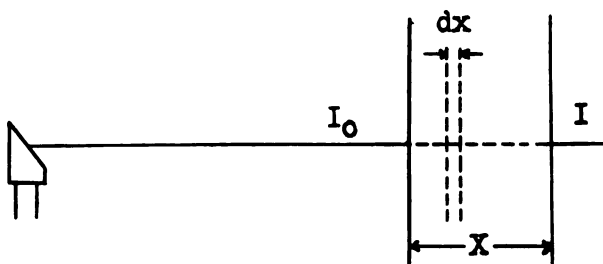


Fig. 54. Diminution of X-Ray Intensity In Matter Placed in the Path of The Radiation.

then be reduced by $I_0 \cdot \mu dx$, or $dI_0 = I_0 \cdot \mu dx$. Since the change in intensity occurs in the reverse direction to the incident beam, we may further express this diminution by

$$dI_0 = -I_0 \mu dx$$

and,
$$\frac{I_0}{dI_0} = -\mu dx \quad (62)$$

Integrating equation (62) from the plane of the slab facing the x-ray tube target to the opposite plane, we obtain

$$\int_{I_0}^I \frac{dI_0}{I_0} = - \int_0^X \mu dx$$

When the thickness X of the slab is equal to zero, then $I = I_0$; and, we may equate

$$\text{Log } \frac{I}{I_0} = -\mu X$$

$$\text{and,} \quad \frac{I}{I_0} = \epsilon^{-\mu x} \quad (63)$$

$$\text{or,} \quad I = I_0 \epsilon^{-\mu x} \quad (64)$$

where, I_0 is the initial intensity of the radiation (primary ray) leaving the tube target, I is the intensity of the emergent beam from the object traversed (intensity reaching the film), ϵ is the base of Natural logarithms, and μ is the coefficient of absorption and x the thickness of the material.

Since we have stated that the absorption of x-rays depends on the density as well as on the thickness of the material, it becomes, then, desirable to express the right-hand side of the equation (64) in terms of the density, too. As the value of a quantity does not change if it is multiplied and divided at the same time by the same quantity, the expression (64) then takes the form

$$I = I_0 \epsilon^{\frac{\mu}{\rho} \cdot \rho x} \quad (65)$$

in which, ρ is the density, and μ/ρ is the mass absorption coefficient of the material in question.

Frequently the absorption properties of different materials are expressed in terms of the *half-value* thickness H . This factor H represents that thickness of the material which will reduce the intensity of a homogeneous beam of x-rays to one-half its initial value. For instance, $\frac{1}{2}I_0 = I_0 \epsilon^{\mu H}$; and, $H = \log_e 2/\mu = 2.3 \log_{10} 2/\mu = 0.69/\mu$. Accordingly, when the coefficient of linear absorption μ for a given x-ray photonic wavelength is known, the thickness of the material to reduce the intensity I_0 of the initial beam to one-half its value is found by dividing 0.69 by the numerical value μ and taking the antilogarithm of the quotient.

In considering, however, an x-ray beam of heterogeneous mixture of wavelengths, the factor $0.69/\mu$ does not hold, owing to the differential absorption of the various wavelengths in the

radiation. That is, assuming that 0.38 mm of copper of uniform thickness reduces the intensity of a given heterogeneous beam of x-rays from, for instance, 100 units to 50 units, the additional thickness necessary to reduce the intensity from 50 units to 25 units (another 50 per cent) will not be 0.38 mm but about 0.7 mm. It is obvious then that in traversing the first 0.38-mm copper a great portion of the less penetrating rays (longer wavelengths) is absorbed so that the transmitted rays possess shorter wavelengths, and hence the necessity of greater thickness of copper in producing an additional 50 per cent reduction in the radiation intensity. Therefore, in order that a linear relationship between thickness and absorption can exist, the original radiation beam must be completely homogenized by adequate filtration prior to the application of *half-value* relation.

The coefficient of absorption μ of any substance may be calculated by the equation

$$\mu = \frac{2.302 (\log I_0 - \log I)}{x} \quad (66)$$

where, the logarithm is given as having a base 10.

When the coefficient of absorption for a given applied voltage is known, the relation (66) may be equated to the thickness value x as

$$x = \frac{2.302 (\log I_0 - \log I)}{\mu} \quad (67)$$

From the above equations, it should be noted that when successive thicknesses of an absorbing material are placed in the path of a homogeneous x-ray beam, the reduction in intensity from, for instance, *1 intensity unit* (arbitrary) to *0.5 intensity unit* requires the same thickness of the material as that from, for instance, *0.8 intensity unit* to *0.4 intensity unit*, or from *60 units* to *30 intensity units*. And, conversely, the same thickness of the material will always produce a diminution in intensity by the same fractional amount. For instance, if 0.25 mm of copper reduces the intensity of a given x-ray beam from 100 to 81.68, which is a reduction of 18 per cent, an additional thickness of 0.25 mm of copper will reduce the intensity from 81.68 to 66.7 intensity units, again a reduction of 18 per cent.

Therefore, in considering the reduction in intensity of the beam when expressed in exponential law, the numerical value for each successive additional layer of the material will be the same. When a curve is plotted with the logarithm of the intensity against the thickness, for instance, in millimeters, a straight-line graph will be obtained, as shown in Fig. 55.

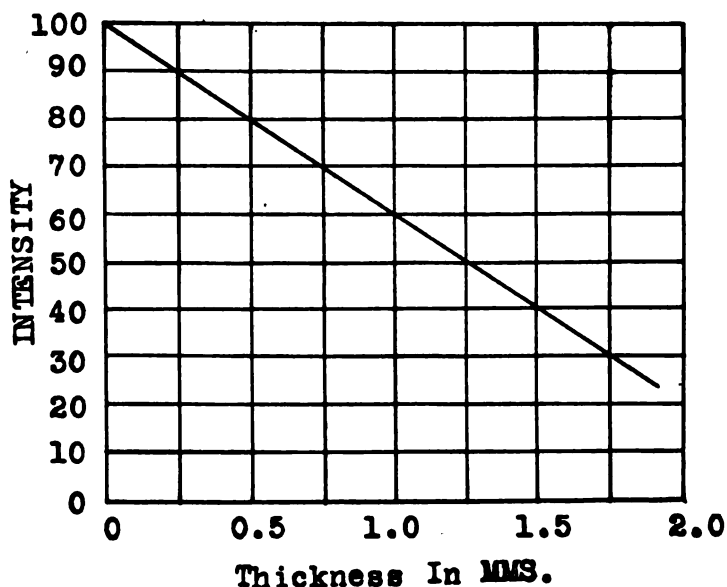


Fig. 55. Illustrating the Absorption of a Homogeneous Beam of X-Rays. Logarithm of Percentage Transmission ($\log 100 I/I_0$) is Plotted Against the Thickness of the Absorbing Material.

Table III gives the x-ray mass absorption coefficients of different materials for various wavelengths of the incident x-rays.

It will be evident then that when radiographing different materials of different densities of same thicknesses, if the exposure technique for one type of material has been established the technique for another material for the same thickness may be calculated simply by a comparison of the densities of the two materials. For instance, as indicated in the chart shown in Fig. 64, it takes 150 kilovolts, 10 milliamperes, and 2.3 minutes to radiograph rolled steel 1.0 inch thick at a focal-film distance of 36 inches. It is desired to know how long it will take to radiograph

TABLE III:—X-RAY MASS ABSORPTION COEFFICIENTS

X-Ray Wavelengths in A. U.	.0200	.081	.102	.151	.209	.240	.320
Carbon	.0582	.143	.150	.153	.166	.170	.200
Aluminum	.0559	.145	.169	.....	.295	.356	.630
Iron	.0549	.235	.280	.595	1.260	1.750	3.950
Copper	.0542	.270	.335	.780	1.710	2.500	5.250
Silver	.....	.740	1.170	2.650	6.500	9.600	21.100
Tin	.0544	.800	1.200	3.150	6.950	10.800	22.000
Tungsten	.0627	2.400	3.500	8.000	3.930	5.100	10.100
Lead	.0672	2.530	3.900	2.450	5.350	7.400	16.200

phosphor bronze of the same thickness (1.0 inch) under identical conditions.

From Table VII, it will be noted that the density of steel is 7.85 grams per Cc and that of phosphor bronze is 9.00 grams per Cc. By formulating an equation in terms of the densities and the thickness of the metal under consideration we obtain for the equivalent thickness T of phosphor bronze as

$$T = \frac{M \times D}{S} \quad (68)$$

where, M is the thickness and D the density of the metal whose exposure technique is to be determined, and S is the density of the metal whose exposure technique is given. Hence, the thickness of steel-equivalent for phosphor bronze of 1-inch thickness will be

$$T = \frac{1.00 \times 9.00}{7.85} \\ = 1.146 \text{ inches.}$$

From thickness chart for steel we find that the exposure time for 1.146 inches of steel exposed at 150 KV and 10 M.A. is approximately 4.8 minutes. Therefore, the exposure for 1.0 inch of phosphor bronze will be 4.8 minutes, or 4 minutes and 48 seconds.

Assuming that in radiographing the 1-inch phosphor bronze 170 KV is employed instead of 150 KV, the new exposure time may be computed by producing a perpendicular from the 1.146-inch thickness scale on the steel chart and taking the point of intersection with the 170-KV curve as the new time of exposure, which will be 1.5 minutes.

Example:—A copper plate of 0.4 cm thick is radiographed by employing homogeneous x-radiation incited by 122 kilovolts. What will be the reduction in x-ray intensity if the incident radiation energy is assumed as 100 arbitrary intensity units?

By using equation (61), and solving for homogeneous (monochromatic) wavelengths produced by 122,000-volt energy, the latter will have an average value of 0.102 angstroms. Consulting Table III, it will be noted that the mass absorption of copper for this wavelength is 0.335. The density of copper is 8.9 grams per Cc.

Hence, we have $\mu/\rho = 0.335$

$$\mu = 0.335 \times 8.9 = 2.98$$

$$x = 0.4 \text{ centimeter}$$

By substituting the numerical values of the quantities μ and x in equation (66) or (67), we may isolate the logarithmic terms to solve for the relative diminution in the intensity of the primary beam.

$$\text{Thus,} \quad \text{Log } I_0 - \text{Log } I = \frac{\mu x}{2.302} = \frac{2.98 \times 0.4}{2.302}$$

$$\text{and,} \quad \text{Log } \frac{I_0}{I} = 0.52$$

Referring to a common logarithmic table, and determining the antilog of the figure 0.52, we find 3.31. This means that the ratio of I_0 to I is respectively 3.3 to 1.

Or,
$$\frac{I_0}{I} = 3.3$$

and, therefore, the emergent intensity I is equal to $I_0/3.3$, or $I = 0.303 I_0$. This last expression simply indicates that the emergent intensity is about 30 per cent that of the incident beam.

It is obvious, now, that when a beam of x-radiation traverses a casting, the sound sections will absorb more of the radiation than the defective sections such as gas cavities, shrinkage fissures, or slag inclusions, since the density of the inhomogeneous (defective) part will be different (smaller in this case) than the sound section. This difference due to lack of homogeneity and hence a difference in density will produce differences in photographic (radiographic) blackening which forms the image in the emulsion of the film. Such an image formed by the x-rays causing different gradations of blackening in the film emulsion is called a *radiograph*. The gradations of the radiographic density together with delineations of contrast details permit the examination of parts radiographed. The phenomenon forms the basis of x-ray inspection of materials of industry.

6. Secondary X-Radiations.—When *primary x-rays* issuing from the target of the x-ray tube become incident upon various materials, the radiation energy in part is transformed into new radiations, and partly scattered as the original radiation. For sake of convenience, any x-radiation from matter other than the x-ray tube target is classified as a *secondary radiation*. Any object placed in the path of the primary radiation will produce, to some extent, secondary radiations. Such objects may be the glass walls of the x-ray tube, the anode stem, the protective shield around the tube, the cone (if there is one), the metal part being radiographed, and any other object in the path of the primary radiation.

Secondary rays, by impinging on other objects, may set up *tertiary x-rays*. Whatever the character of the resulting radiation may be, it must be well clear in mind that the energy of the inciting x-rays associated with either secondary or tertiary radiations must be equal or greater respectively than the incited secondary or tertiary radiation before an emission can take place. Our scope in this text, however, will be limited to the discussion

on two types of secondary radiations—namely, *scattered radiations*, and *characteristic radiations*. The two radiations, singularly or together, present problems especially in radiographing metals of high atomic number that it appears, of necessity, to study the true character of each in order to eliminate the precarious effect that they may produce in a radiograph, interfering with the true image delineation and hence with accurate interpretation of the radiograph.

(a) *Scattered Radiations*.—Primary x-rays when incident upon organic matter, such as wood, cardboard, wax, film, bakelite, etc., or, upon aluminum and other metals having an atomic number below that of aluminum, a part of the rays pass through the object without transformation, while the other part may be scattered in random directions. The scattered rays have wavelengths practically of the same magnitude as the primary rays, and therefore possess the same photochemical effects as the primary beam inciting them. Hence, if the scattered rays are allowed to reach the photographic film they will impart to the latter a general haziness by distorting the image, interfering with the otherwise clear, well-defined, and sharp details of the radiographic image. The effect is due to the impinging of the secondary rays onto the film from directions other than that of the radial primary beam projecting directly from the target of the x-ray tube.

One way of effecting a considerable diminution in the scattered radiation is to employ a high-voltage rapid exposure technique. Though the increase in voltage above that optimum may somewhat curtail the contrast quality of the radiograph, the resultant gradations in the radiographic density to warrant ready visibility of detail delineation will more than offset the disadvantage presumably occurring from the high-voltage technique.

The scattered radiation consists, in general, of the secondary rays having the same wavelength as that of the primary ray and those having slightly different wavelengths from those of the primary rays. The former type of radiation is known as the *unmodified rays*, and the latter having relatively longer wavelengths is known as *modified rays*.

When a primary beam of moderate wavelengths falls on light metals there may occur a change in the wavelengths of the scat-

tered radiation, and this change is dependent on the angle between the primary beam and the scattered rays under observation. A. H. Compton has shown that the increase in wavelength, $\Delta\lambda$, of the incident radiation subsequent to scattering is 0.0243 angström for the extreme case.

The effect may be explained by a reference to the laws of conservation of energy and of momentum. Assume that a primary x-ray quantum of energy hf_0 collides with an electron in the secondary emitter and imparts to it a small amount of kinetic energy. As a result, the electron will recoil in a direction making an angle ϕ . The quantum itself proceeds with an energy hf and at an angle θ with the initial direction. It is then obvious that the radiation energy hf deviated from its normal course will possess an energy, and hence a wavelength, less than hf_0 by an amount involved in the collision with the recoil electron.

In accordance with the law of conservation of energy, we may express the relation of energy transfer by

$$hf_0 = hf + mc^2 \left(\frac{1}{\sqrt{1 - \beta^2}} - 1 \right) \quad (69)$$

in which, h is Planck's constant equal to 6.55×10^{-27} erg-second, f_0 is the frequency of the incident photon, f the frequency after collision, m the mass of the recoil electron equal to 9.107×10^{-28} grams, c the velocity of light (3×10^{10} cms per second), and β is equal to v/c , the ratio of the velocity of the recoiling electron to that of light.

It must be noted that the incident quantum of energy hf_0 will possess a momentum equal to hf_0/c ; and, after collision with the electron the momentum of the deviating quantum will be hf/c . Computing for the momenta for the x and y directions, we may equate

for the x -component of the momentum

$$\frac{hf_0}{c} = \frac{hf}{c} \cos\theta + \frac{m\beta c}{\sqrt{1 - \beta^2}} \cos\phi \quad (70)$$

in which, θ is the angle between the scattered ray and the incident ray, and ϕ is the angle between the recoil electron and the initial direction of the radiation quantum hf_0 .

And, for the y-component of the momentum, we have

$$0 = -\frac{hf}{c} \sin\Theta + \frac{m\beta c}{\sqrt{1-\beta^2}} \sin\Theta \quad (71)$$

By combining equations (69), (70), and (71), and by a process of elimination and substitution, we may arrive at an equation involving the incident and the scattered wavelength values. Thus, we have

$$\lambda - \lambda_0 = \frac{h}{mc} (1 - \cos\Theta) = \Delta\lambda \quad (72)$$

where, λ is the wavelength of the scattered quantum, λ_0 that of the incident radiation, and $\Delta\lambda$ is the change in wavelength between the incident and the scattered rays.

By substituting the numerical values of the three constants h , m , and c , in equation (72), we obtain for the change in wavelength

$$\Delta\lambda = 0.0243 (1 - \cos\Theta) \quad (73)$$

where, Θ is the angle between the primary and the scattered x-ray photons.

From the last equation it will be evident that when the angle of scattering is 90 degrees (cosine of 90 degrees is equal to zero) the shift in wavelength will be 0.0243 angstrom. For instance, if a primary x-ray quantum of wavelength 0.132 angstrom becomes scattered from an object at 90 degrees, its wavelength will increase to $0.132 + 0.0243 = 0.1563$ angstrom.

The energy with which the recoiling electron proceeds may be calculated by a reference to equation (72), in which the change of wavelength $\Delta\lambda$ is given as

$$\Delta\lambda = \lambda - \lambda_0 \quad (72)$$

Putting the above relation in terms of the corresponding quanta energies, we obtain

$$\Delta \frac{hc}{\lambda_0} = \frac{hc}{\lambda_0} - \frac{hc}{\lambda} \quad (74)$$

If we assign ΔE for the kinetic energy of the recoil electron in substitution for $hc/\Delta\lambda$, we obtain for the extreme case of quantum deviation (which is 90 degrees) an expression given by

$$\Delta E = \frac{hc}{\lambda_0} - \frac{hc}{\lambda_0 + 0.0243} \quad (75)$$

or,
$$\Delta E = hc \left(\frac{1}{\lambda_0} - \frac{1}{\lambda_0 + 0.0243} \right) \text{ ergs.} \quad (76)$$

Substituting the numerical values of h and c , in equation (76), and converting the resultant energy in ergs into volts (1 electron-volt = 1.59×10^{-12} erg) we may compute the energy of the recoil electron for any given voltage applied to the x-ray tube.

(b) *Characteristic Radiations.*—When a beam of primary radiation becomes incident upon the metal parts of the x-ray apparatus, or, upon a casting or part under exposure and having an atomic number greater than aluminum, an emission of secondary radiation having a quality (wavelengths) independent of the incident radiation is observed. The wavelength of this type of secondary emission depends on the atomic number, or, more precisely, on the critical or quantum frequency f_0 of the metal radiated; and, therefore, the quality of the radiation is thus said to be characteristic of, and strictly dependent on, the secondary emitter (a casting, or any metal part). Heavy metals, such as steel, iron, copper, bronze, and alloys of heavy elements are principal sources of characteristic secondary radiations.

Before a metal is capable of emitting a characteristic radiation, the inciting primary beam which gives rise to the emission must possess a frequency f equal or greater than the critical (threshold) frequency f_0 of the emitting metal. That is, the energy hf of the primary x-ray photon must be equal to or greater than the energy hf_0 of the secondary photon ($hf > hf_0$) in order that a secondary quantum emission may be realized. Accordingly, an x-ray photon having a wavelength, for instance, 1.28 angstroms cannot incite a characteristic quantum radiation of 1.2 angstroms, because the energy hf of the former photon is less than that of hf_0 of the latter photon. That is, the frequency f is smaller than the frequency f_0 of the secondary photon, h being constant in both cases. This type of secondary radiation is identical with fluorescent characteristic rays.

To produce characteristic radiations by means of electrons in an x-ray tube requires sufficiently high voltages. For instance, in an x-ray tube having a tungsten focus a potential of the order of 75 kilovolts is necessary before a *K* characteristic radiation is emitted. The voltage required to incite the atom to a characteristic radiation is proportional to the square of the atomic number of that atom. For instance, tungsten has an atomic number of 74, and molybdenum has one of 42. The energy required to incite a molybdenum target to characteristic radiation will be

$$\frac{42 \times 42}{74 \times 74} = \frac{1}{3} \text{ (approx.)}$$

which means that about 25 kilovolts will incite a molybdenum target to characteristic emission. If the voltage required to cause the emission of a characteristic radiation from a given atom is known, this voltage for other atoms may be readily computed by the relation shown in the foregoing example.

(c) *Absorption and Scattering Coefficients*.—It has been already pointed out that when a beam of x-rays becomes incident upon matter, the radiation energy becomes partly absorbed and partly scattered. Reference has also been made as regards the use of mass absorption coefficient μ/ρ in that the quantity is independent of the physical state of the substance traversed by x-rays, whereas the linear absorption coefficient μ is not. The latter is a direct function of the physical properties such as gaseous, liquid, or solid states of the substance.

In the mechanism of absorption, the phenomenon may be resolved into two components—the true mass-absorption coefficient τ/ρ , and the mass scattering coefficient σ/ρ . The value of the latter quantity which represents the energy expended in the production of unmodified scattered x-rays, modified scattered x-rays, and Compton electrons, is relatively smaller than the true or fluorescent mass-absorption coefficient τ/ρ which accounts for the loss of the radiation energy due to characteristic x-rays and photo-electrons. We may then express the relation of these quantities in an equation form as

$$\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma}{\rho} \quad (77)$$

in which, τ is the true absorption coefficient and σ the scattering coefficient of the substance under consideration.

While the quantity σ/ρ varies slowly with increasing wavelengths, the mass-absorption coefficient due to fluorescence, τ/ρ , increases rapidly as the atomic number of the absorbing element and the wavelengths of the radiation increase, in accordance with Bragg-Peirce law, which may be written as

$$\frac{\tau}{\rho} = C \frac{Z^4 \lambda^3}{A} \quad (78)$$

where, Z is the atomic number of the absorbing element, A its atomic weight, λ the wavelength of the incident monochromatic x-radiation, and C is a constant between two successive critical absorption wavelengths and changes at wavelengths characteristic of the element. It is evident, then, from equation (78) that τ/ρ is large for elements of high atomic weight and for long wavelengths, but becomes smaller with lighter elements and shorter wavelengths because of the rapidly decreasing value of λ^3 . Hence, μ/ρ for heavy elements irradiated by x-rays having long wavelengths becomes correspondingly large as the values of τ and λ become large.

As has been explained previously, before an emission of characteristic fluorescent radiation occurs the incident quantum must possess a minimum energy of frequency f_0 (critical frequency), and that all this energy must result in the appearance of a characteristic wavelength. The latter wavelength, at which the characteristic series starts, is known as the *critical absorption wavelength*. The significance of the critical absorption wavelength may be better illustrated by a reference to the curve shown in Fig. 56.

As the wavelengths increase toward point A , Fig. 56, the absorption increases correspondingly until the critical point of characteristic wavelength λ_{ϵ_1} is reached. At this value of the wavelength a sudden drop in the absorption occurs. Just beyond the critical wavelength, the absorption continues until the point B is reached with a consequent occurrence of λ_{ϵ_2} and a drop in the absorption. With continued change in wavelengths the points C , D , and E are reached at corresponding wavelength values of

λ_{L_1} , λ_{L_2} , λ_{L_3} . The phenomenon continues until all the characteristic wavelengths of the element are emitted with consequent drop at each occurrence of the critical wavelength. It must be kept well in mind that while characteristic wavelengths are emitted at critical absorption states of the atom, there occurs

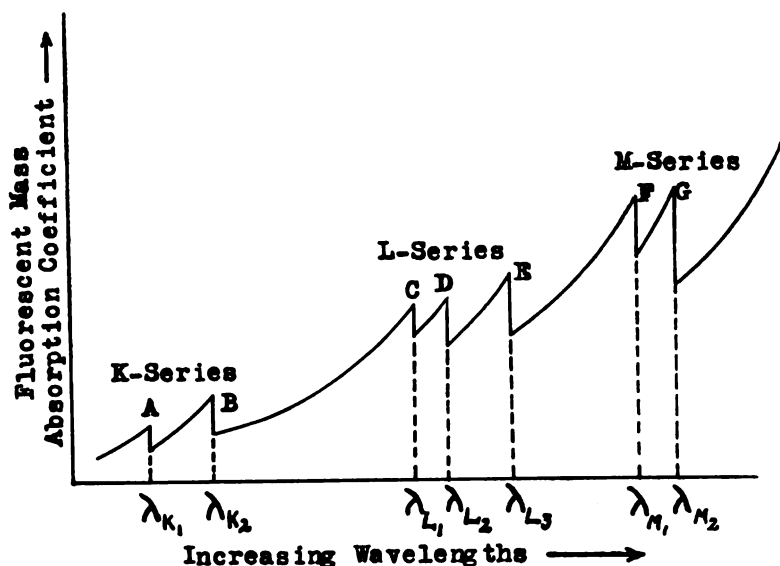


Fig. 56. Illustrating the Change in Absorption in a Metal with Increase in Wavelength.

also a continuous spectrum of wavelengths from these *K*-, *L*-, *M*-, *N*-, etc. orbits with the orbital transition of the electrons possessing energies corresponding to various atomic excitation levels. The two spectra, *characteristic* and *continuous*, occur superimposed.

7. Partial Elimination of Secondary Radiations.—In industrial radiography, secondary radiations especially from metals of high atomic number (heavy metals) become of great concern, as the resulting radiograph is not exempt of over-all haziness or detail unsharpness. There have been devised various methods for discriminating the secondary radiations (at least to some extent) from the film exposure field. The simplest, yet an effective method, is by the use of *filters* and metal *intensifying screens*, which consist of thin foils of lead, antimony, tin, zinc,

copper, and the combination of any two or three in separate sheet forms or in alloy forms.

In the case of a large exposure field employing a 14" x 17" film, the scattering of the radiation will become more prominent. To eliminate the secondary radiation and thus to obtain the optimum sharpness, a device known as *Bucky diaphragm* may be interposed between the film and the object to be radiographed. The device comprises a moving grid consisting of alternate rows of lead strips of radiotransparent material such as wood, fiber, or bakelite. Wood is preferred by general practice. During exposure, the grid oscillates back and forth and intercepts those rays which proceed toward the film from directions other than the x-ray tube target. Since secondary radiations result from random directions, they are stopped by the lead strips of the grid by becoming absorbed by the lead atoms.

Small fabricated parts may be immersed in a solution of heavy elements, such as lead nitrate, lead acetate, stannous chloride, barium nitrate, barium chloride, or in organic compounds such as methyl iodide, carbon tetrachloride, methylene bromide, etc., and radiographed by usual methods. The author has successfully used a supersaturated aqueous mixture of lead nitrate and lead acetate for steel, bronze, cast iron, etc., that the resulting radiograph not only indicated finer gradations of the metal but also complete elimination of the secondaries from the field. Usual radiographing of such parts would have resulted in the complete diffusion of the various thickness gradations with profuse darkening effect indicated especially around the edges and contours of the part under examination. In using any one of these solutions, care should be taken that the part immersed into the solution does not enter into a chemical reaction with it. In the latter case, the object should be impregnated with paraffin previous to immersion. Subsequently the paraffin may be removed by benzene.

Barium or bismuth clay, lead shots, copper shots, copper powder, and heavy sheets of lead may be employed to shield the part of the metal which is not required to be shown in the radiograph but is immediately adjacent to the section to be radiographed. The success of any one of the above methods depends principally on the skill and manipulation of the radiographer. With

several trials proper technique may be acquired that ultimately will warrant the inconvenience and time spent in mastering this skill.

8. Measurement of X-Ray Intensity, and Wavelengths.—

It has already been discussed on a previous occasion that the intensity of x-rays produced in an x-ray tube is a function of the effective tube current and the voltage applied to the tube. Under most favorable conditions the radiation output from a target of high atomic number in an ordinary diagnostic x-ray tube is between 0.25 to 0.30 per cent that of the energy of the input power. For potentials ranging from 500 to 2000 kilovolts, the output amounts to about $2\frac{1}{2}$ to 10 times respectively. From both empirical relations and observations based on actual experimental results it is concluded that the yield or the intensity of x-rays is approximately proportional (in the optimum case where the wavelengths of the characteristic radiation and the continuous spectrum are superimposed) to the square of the applied tube tension. The efficiency of the yield is further dependent on the atomic number of the target material.

From above inferences it would appear that if an x-ray tube is energized with voltages as high as one million volts or over the x-ray yield will be markedly improved. This is invariably the case, for x-rays generated at 1000 kilovolts and 3 milliamperes have an intensity equal to 100 grams of radium as against a few milligrams of radium equivalent to x-rays incited at voltages up to 200 kilovolts.

X-rays effect ionization in a gas which they traverse. Advantage is taken, therefore, in utilizing this property in the quantitative measurement of the radiation intensity by employing an ionization chamber. The method is known as *ionization spectrometry*. A simple ionization spectrometer, shown in Fig. 57, consists essentially of a crystal table which rotates on its axis with reference to an angular scale graduated in degrees, minutes, and seconds. An ionization chamber, *C*, (consisting of two electrodes and a small amount of easily ionizable gas) measuring several centimeters long and about 1 centimeter in diameter is mounted on the rotating table. The chamber has a metal plate (electrode) *P* extending axially within the cylin-

derical chamber and well insulated from the walls (which constitute the second electrode) of the latter at S .

At one end of the tube is a window W covered with a thin sheet of aluminum or mica which serves as a port of entry of the

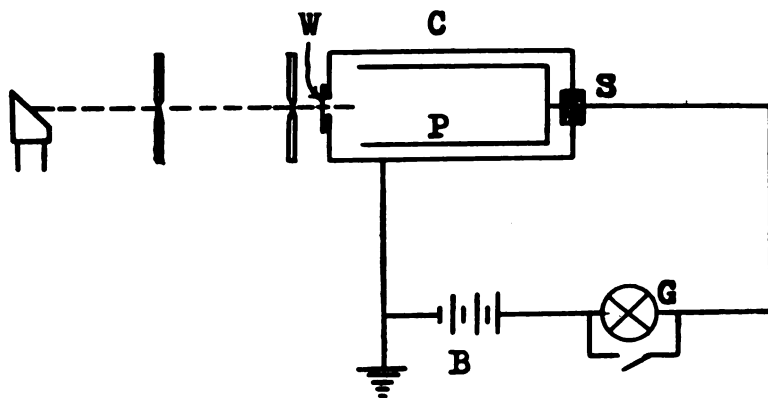


Fig. 57. The Ionization Spectrometer for the Measurement of X-Ray Intensity.

x-ray beam whose intensity is to be measured. An electric field of 250 to 500 volts per centimeter is maintained, from a direct current source B , between the plates P and the walls C of the chamber. When x-rays are made to pass into the chamber, the gas within becomes ionized, charging the respective electrodes comprising the plate and the walls of the chamber. The rate of accumulation and the magnitude of the charge is measured by a sensitive galvanometer G . This charge is a measure of the intensity of the x-ray beam at a specified distance from the x-ray tube.

At present, there are various types of commercial instruments devised to measure x-ray intensity. Most common of these are the x-ray dose measuring devices, and stray radiation recorders, such as, for instance, the Victoreen Iometer, and the Mecapion, manufactured by the General Electric Company. The latter instrument is an integrating dosimeter utilizing both the primary radiation entering the ionization cell and the secondary electrons, and is independent of the wavelengths included in the incoming x-ray beam. It measures the radiation intensity in *r-units*. The ionization current produced in the instrument is

usually measured by means of a gold-leaf electroscope or by the deflection per second of a quadrant electrometer. A more elegant scheme employs an amplifying unit which, when calibrated, indicates the intensity in either r-units or as ionization current.

In the measurement of x-ray wavelengths the ionization spectrometer plays an important part. Following Laue's discovery of diffraction of x-rays by the cleavage planes (crystal faces) of crystals, the first practical and reasonably accurate x-ray spectrometer was developed by W. H. and W. L. Bragg. The instrument fundamentally serves to measure the angle between the cleavage surface of a given crystal and the x-ray beam. In conjunction with the crystal, and the graduated table on which it is mounted, an ionization chamber is employed to determine the position and the intensity of the reflected, or the emergent, rays (depending whether the x-ray beam is angularly or normally incident on the crystal respectively) in accordance with the variations of the deflections of the measuring instrument. The essential working parts of an x-ray spectrometer of the Bragg type is illustrated in the diagram shown in Fig. 58.

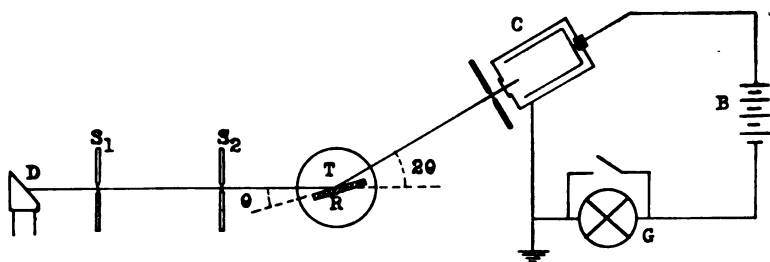


Fig. 58. Schematic Diagram of the X-Ray Spectrometer.

A beam of x-rays, incited by about 40 to 50 kilovolts, from the target *D*, is collimated by slits *S*₁ and *S*₂ into a fine pencil, and allowed to fall at a glancing angle upon a crystal *R*, such as calcite, rock salt, quartz, gypsum, or mica, mounted on a rotating table *T*. The reflected, or, the emergent, beam is made to enter the ionization chamber *C*, which is impressed from the high voltage source *B*. The chamber is also mounted on a rotating table (not shown in the figure) so that it can be rotated radially to the axis of the crystal for locating the beam of x-rays reflected from the crystal. Since the reflected beam makes

an angle 2θ with respect to the incident beam, and knowing the distance d between the two adjacent cleavage planes of the given crystal, the wavelength of the incident radiation may be computed by the well-known Bragg formula.

$$\lambda = \frac{2d \sin \theta}{n} \quad (79)$$

where θ is the angle between the incident x-ray beam and the crystal cleavage face, and n stands for the spectral order of the wavelengths. The numerical value of d for rock salt is given as 2.814 angstroms, for calcite 3.029 angstroms, for quartz as 4.246, and for mica it is 9.942 angstroms, at a temperature of 18°C .

Due to thermal expansion of the crystal under investigation, the cleavage distance d of the crystal is usually taken for observation made at 18°C . Another correction factor, which is not taken into consideration in equation (79), is the slight refraction of the x-ray beam as it passes through the crystal. Thus, we may express the corrected relation by including in the equation (79) the index of refraction μ of the crystal. The expression, then, becomes

$$\lambda = 2d \sin \theta \left(1 - \frac{1 - \mu}{\sin^2 \theta}\right) \quad (80)$$

For x-rays incited by voltages anywhere below 65 kilovolts (effective) the radiation is usually made to fall at glancing angles to the surface of the crystal (which may be replaced, if desired, by a ruled grating), whereas for higher kilovoltages the x-ray beam is allowed to become incident normally with the cleavage plane of the diffracting material. In general, a photographic recording of the different wavelengths of the x-ray beam is made by replacing the ionization chamber by a photographic plate or film. The various positions and the intensity of blackness of the line spectrum formed on the film are a measure respectively of the magnitude of the wavelength and the intensity of the radiation, compared with a standard spectrograph.

A combination of equation (61) and equation (79) may be employed to measure the peak voltage of a given x-ray radiation, by substituting the value λ in equation (61) for $2d \sin \theta$ in

equation (79). Thus, we have

$$V = \frac{12345}{\frac{2d}{n} \sin \theta} \quad (81)$$

where V is the applied voltage to the x-ray tube.

9. Electrical Safety and X-Ray Protection.—The problem of complete electrical and x-ray protection from a practical standpoint has long been the object of x-ray engineers, and research toward this end has been extended throughout the laboratories the world over, until the search fundamentally has terminated with the introduction of the first commercially available ray-proof tube in the year 1927. The new development is further superseded, in the following year, with the incorporation of a grounded metal sheathing around the entire x-ray tube to offer the advantage of absolute protection against high tension hazards. Following this trend, practically all x-ray tubes of modern manufacture are provided with protection against both the high-tension and stray radiations from the x-ray tube.

Prior to recent introduction of modern safety on standard x-ray equipments, various protective devices, such as sheet lead, plumbized rubber aprons and gloves, lead-glass shields partially surrounding the x-ray tube, and lead-glass protective screens, were supplied with every x-ray machine by the manufacturer. But, such means did not provide the necessary safety of the operator, since serious damage by accidental contact with the high tension lines or by excessive exposure to x-rays were reported not infrequently. Hence, the necessity for limiting the situation to the confines of absolute electrical and x-ray safety has given impetus, with the cooperation of the International X-Ray and Protection Committee with manufacturers of x-ray equipment, to the gradual but steadily advancing development of the ultimate protective measures.

(a) *Protective Measures From Electrical Hazards.*—While the electrical safety aspect of the question lends itself to the design, constructional detail, and the material of the equipment built on the discretion of the manufacturer, the problem has by no means been met with an easy solution; for instance, for the

provision of a simple and practical tube shielding, which will afford, at the same time, an adequate system for dissipating the heat generated during the operation of the x-ray tube; for the installation of overhead aerials which will produce practically no corona discharge; for insulation of the x-ray personnel from ground by providing adequate floor covering; for efficiently grounding all independent electrical circuit systems, metal parts of the apparatus, etc.

Wherever possible, shock-proof x-ray equipment is highly recommended for the safety of the operator (and for the patient in the case of medical practice). Distinctly indicating the main and supply switches by means of pilot lights or by some other readily distinguishable sign is found to be of aid in the elimination of electrical hazards. The push-button or the foot switch to energize the x-ray tube should be of such design as to make it incapable of accidental closure, and that these should be encased in vapor-proof receptacles. Since any exposed high voltage parts have the tendency of generating gases, such as nitrous oxide, ozone, etc., adequate ventilation should be provided in order to maintain a hygienic condition among those concerned in the x-ray room.

In order to render an electrical contact with live studs or metal parts practically impossible, the control handles of all x-ray units are invariably of insulating material. In addition to the provision of insulations surrounding the control knobs all flexible conductors used in the low tension circuit of the apparatus are adequately insulated with rubber sheathings. Since these conductors are constantly subject to inadvertent handling, kinks may form at connection points, causing the insulation to become susceptible to breakdown and to exposure of bare wires, which may become a potent danger to human contact. The latter hazard may be minimized, however, by adopting small voltages for all control circuits from appropriate autotransformer tap-pings.

Earthing the x-ray primary circuit produces a material reduction in electrical hazards but such must not be regarded as absolute immunity to electrical shocks. The condition is one of diminution in the magnitude of the shock (if such be re-

ceived) and cannot be predetermined whether or not it will meet with adverse consequences.

During operation of the x-ray tube, the secondary circuit of the x-ray transformer is sustained at a high potential. The condition is a potent source of danger wherever there is a possibility of accidental contact with a live conductor. However, contrary to common concept, the effect is not always the more dangerous the higher the voltage, as fatal consequences as a result of contact with voltages as low as 40 volts are reported as having occurred. Hence, no conclusion can be drawn with reference to safety limits of potential. It is true, however, that a direct or a constant-potential current is more dangerous than a pulsating or an alternating type. In general, a high frequency current is less dangerous than a low frequency energy. In this connection it will be further noted that a transformer associated with pulsating rectified currents, such as produced by a mechanical rectifier or by valve-tube alone is more dangerous than that connected across a rectifying set employing condensers in conjunction.

X-ray practice in this country requires the embodiment of a ground lead generally at the center of the high-tension transformer secondary. The scheme aims at reducing the risk of a high voltage electric shock on the assumption that smaller tensions would be safer to guard against. Since, by grounding the secondary in the middle, each of its two divided sections develop one-half the entire transformer potential, a shock received at this magnitude may produce materially less hazardous consequences. The latter procedure further reduces the voltage insulation problems to one-half the value that required to effect an insulation to full transformer voltage.

There are a number of commercially available devices for the purpose of cutting off the supply current to the x-ray generator should an accidental human contact occur with the high tension circuit. Of these, various types of electrosensitive relays, tripping gears, automatic circuit breakers, etc.—some furnished in conjunction with visual or auditory signal means to give warning prior to actual contact—have been in use for many years with favorable performance. One manufacturer's product employs a sensitive relay whose electromagnetic winding is in

series with the center-grounded lead of the high-tension transformer secondary. During normal operation of the transformer this terminal is at ground potential, and, therefore, no current flows through the relay winding. But, when an accidental connection is made between any portion of the high-voltage circuit (excepting the center-grounded point of the transformer) and the ground, the relay immediately becomes energized, and, in turn, actuates a circuit breaker connected in the primary circuit of the x-ray transformer, thus shutting off the current to the high-tension circuit. The device is designed to minimize the effect of the contact with high voltage and cannot possibly prevent its occurrence. Furthermore, a device of this type should be frequently tested for proper performance, by substituting a 100,000-ohm resistance for human contact ground.

In the manufacture of modern x-ray equipment, however, the impetus is given to the production of an apparatus which makes a dependable safety provision where the possibility of an accidental or intentional contact with any live conductor in the system is impossible under ordinary conditions. Full protection against high tension is achieved by immersing the transformer in an adequately grounded vessel filled with oil, by completely surrounding the x-ray tube with a grounded metal casing, and by providing heavily insulated flexible cables for making connection between the high-tension transformer and the x-ray tube. The instrument panel, the control handles, and the stand are well insulated. Further protection is offered by grounding the x-ray table and hood, which procedure eliminates the possibility of accumulation of electrostatic charges on the apparatus due to the ionized air in the surrounding of the machine. It is only through adhering to the enforcement of the application of these safety provisions that the ultimate electrical protection in x-ray practice is assured.

(b) *X-Ray Protection.*—X-rays have definite influence upon living tissues. It is believed that moderate exposure dosages may accelerate the life cycles of the cells while excessive amounts tend to produce erythematous effects or necrosis of the cells. On this latter concept the treatment of carcinous tissue is based in that the process of the life-cycle of the malignant cell is accelerated, bringing about cellular degeneration as the expected

end result. The application of roentgen rays to producing sterility in human beings by rendering the germ cells infertile has been widely used by roentgenologists, but the condition has been only temporary. The offsprings of the parent organism, who has become subject to such a treatment, have generally not survived with normal characteristics.

Indiscriminate exposures to x-rays may produce erythematous effects in the skin or in the deep-lying structures, depending on the degree of penetration of the radiation. The chief determinant as to whether the cellular degeneration will occur in the superficial or in the deep-lying tissue structures is the effective wavelengths of the roentgen rays. Indeed, various tissues present varying degrees of sensitivity to the radiation. Polymorphonuclear cells exhibit the most radiosensitive characteristics whereas nerve and fat cells are affected the least by x-rays, as will be evident from Table IV.

TABLE IV:—RELATIVE SENSITIVITY OF A NORMAL TISSUE
TO RADIATION OF MEDIUM HARDNESS (HIRSCH)

Leucocytes:	Dermal structures:
2.5 Lymphocytes	1.4 Hair Papillae
2.4 Polynuclear	1.3 Sweat Glands
Germinal Cells:	1.2 Sebaceous Glands
2.3 Ovarian	1.1 Mucous Membrane
2.2 Testicular	1.0 SKIN
Blood-Forming Organs:	0.9 Serous Membrane
2.1 Spleen	Viscera:
2.0 Lymphatic Tissue	0.8 Intestine
1.9 Bone Marrow	0.7 Liver, Pancreas
Endocrines:	0.6 Uterus, Kidney
1.8 Thymus	Connective Tissue:
1.7 Thyroid	0.5 Fibrous Tissue
1.6 Adrenal	0.4 Muscle, Fibrocartilage
Blood Vessels:	0.3 Bone
1.5 Endothelium	0.2 Nerve Tissue
(intima)	0.1 Fat

The radiation renders the nuclear membranes of the living cells more permeable to the absorption of water than the dilution of the cell plasma with the resultant diminution in its con-

centration and osmotic pressure are indicated. The condition gives rise to hemolysis in erythrocytes (red blood cells) with consequent low blood pressure and anemia, and to leucopenia by lowering the number of leucocytes (white blood cells). Further symptoms of x-ray injury are indicated in the thickening of the capillary vessels, inhibition of enzymatic secretion, increase in hydrogen ion concentration (hence, causing acidosis in tissues), retardation of the glandular functions and of the division and growth of embryonic cells, disintegration of the cells constituting the hair follicles, desquamation of the epithelial cells, etc. The skin and the genital organs are extremely sensitive to x-rays.

Since the effect of x-rays is cumulative, impunity of those who are exposed daily to the radiation is impossible. Moderate exposure to x-rays is not harmful, but overexposure may result in desquamation (x-ray burns) of the superficial structures followed by severe dermatitis. In more advanced cases of the disease carcinous ulceration or sloughing of the deep-lying structures may occur. The condition is extremely painful, and unfortunately there is no known remedy to cure or even temporarily arrest the progress of the disease. If, however, the condition in the case of superficial structures is not far advanced some relief may be obtained by exposing the affected area to long-wave ultra-violet rays in gradually increasing doses.

With modern x-ray equipment practically it is impossible to contract acute injuries from x-rays, as the generator is fully protected against the possible dissemination of the radiation from the x-ray tube. However, there are still in use older types of x-ray apparatus which do not provide proper protection against x-rays. The operator of this type of machine appears to be constantly menaced by a tendency to undue exposure to x-rays. Negligence of the operator to screen himself from the radiation field by means of, for instance, lead screens, lead-impregnated aprons and gloves, etc., will expose him to the prevalent danger of x-ray "burns." The "burns" are produced principally by the absorption of long-wave (soft) x-rays constituted partially by direct radiation from the tube and partially by secondary radiations. The former group may be easily screened off by providing adequate ray-proof shielding about

the entire length of the x-ray tube, with the exception of the port of emergence of the useful radiation. Further adequate x-ray protection from an unshielded x-ray tube may be obtained by a lead screen 3-mm thick, or by its equivalent (lead-impregnated rubber—12 mm, or lead-glass—20 mm).

(c) *Permissible X-Ray Dose.*—While in recent years indisposition of health instituted by cumulative effects of exposures to small doses of x-rays are rarely met, nevertheless the subject of permissible x-ray dose cannot escape the attention of the layman who is constantly seeking to collect comprehensive data as regards the dreaded effects of x-rays on organic system in an attempt to adopt increased precautionary measures to minimize the dangers that are attendant as a result of undue exposure to the radiation.

Though the data regarding the amount of radiation to produce harmful effect is not complete, due to varying sensitivity of different individuals, the proposed *permissible dose (tolerance dose)* that can be safely absorbed in the human body ranges from 0.2-r to 0.288-r per sq. cm. of the body surface per day of 8 working hours. The estimates are based on the consideration of dosage for producing a distinct reddening of the skin, or *erythema reaction*, one week after the exposure. This dose is *specific* for each individual and is measured in *roentgens* (r). A roentgen, usually denoted by r, is that unit of x-ray quantity which, when the secondary electrons are fully utilized and the secondary radiation from the wall of the chamber is avoided will produce in 1 Cc of air at standard conditions (760 mm mercury pressure and at 0°C.) one electrostatic unit of charge, or $1/3000$ microcoulomb, equal to an ionization current of 3.33×10^{-10} ampere.

The amount of radiation required to produce an erythema reaction is known as one *skin erythema dose* (TED). In absolute units, this is equivalent to 600-r to 850-r for high voltage ranges, depending upon the physical disposition of the individual to x-rays and upon the voltage at which the radiation is incited. With the quality of radiation usually employed in radiographic work the *threshold erythema* (TED) is calculated as 300 to 400 roentgens.

A convenient equation expressing the erythema time in minutes is given in the following relation:

$$T. = \frac{t \times r}{K \times 60} \quad (82)$$

in which $T.$ is the erythema time in minutes, t is the discharge period of the ionization chamber and is given in seconds, r is the number of roentgens required to produce an erythema, and K is a constant of the instrument in r per full scale deflection.

It is estimated that approximately one-third of erythema dose calculated at higher voltage range will be effective in producing temporary sterility in the genital glands of the male, and about one erythema dose will cause permanent sterility. The irradiation of the ovaries for one-third erythema dose will be sufficient in effecting permanent sterility in the female.

A. H. Compton has shown that at operating voltages of 50,000 volts, the unfiltered radiation intensity at a distance of 1 meter from the target is 1.2 roentgens per second. At 70,000 volts, the r -output for the same distance is only 50 per cent that with 50 kilovolts; from 100 to 200 kilovolts the r -output is about 1/3rd; at 500 kilovolts, it is same as at 50 kilovolts; and at 1-million volts and at 2-million volts, the r -output is respectively 2 and 4 times. From this, one should derive a general idea as to the r -output of various x-ray tubes at various operating potential ranges.

Since absolute protection against x-rays is practically an impossibility, those engaged in x-ray work are constantly subject, to some extent, to exposure to the disseminated radiation limited only by the protection afforded by the clothing worn and the area it covers. A convenient method of determining the radiation quantity received daily is the one that affords qualitative measurement photographically on a film. The method further gives an index as regards the efficiency of x-ray protective power of the shield surrounding the x-ray tube. For either purpose, the operator may fasten a paper clip on a dental x-ray film packet and place several of these at various distances from the x-ray tube, also himself carrying one in his breast pocket, with the lead-lined surface toward his body, for a period of two weeks. If the developed film definitely shows the image of

the clip surrounded by a definitely contrasty field, necessity for increased protective measure is indicated. If an x-ray dosimeter, such as G-E Iometer, or Minometer shown in Fig. 59, is available the ionization method of measurement will give a more accurate index of the stray radiation.

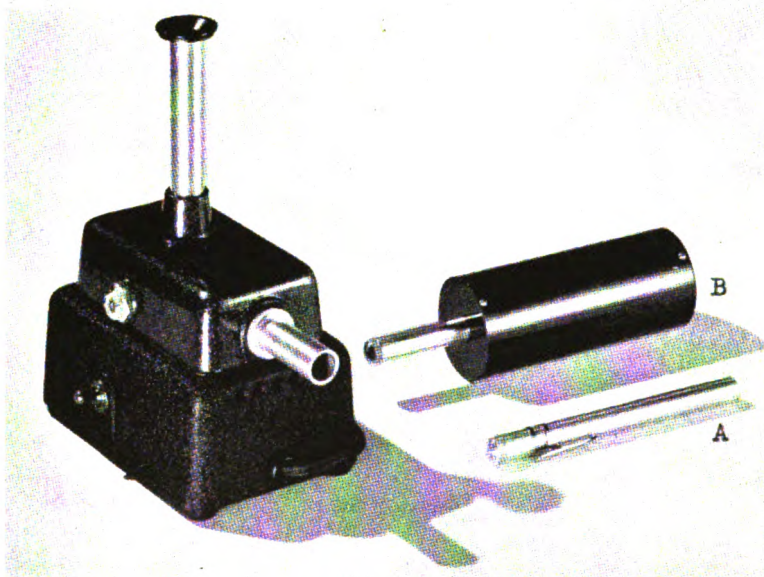


Fig. 59. The General Electric Minometer for the Measurement of Stray X-Radiations.

The *Minometer* is an instrument for measuring the stray radiations from an x-ray generator. It is also used for the detection and measurement of extremely small quantities of x-rays and gamma-rays from radium. The essential parts of the instrument consist of a small string electrometer and an ionization chamber which is interchangeable with any number of ionization chambers of various roentgen capacities.

The electrometer is furnished with a double scale, and is calibrated to read from 0 to 0.1 roentgen when the small fountain-pen size ionization chamber, marked by *A* in Fig. 59, is employed, and from 0 to 0.01 roentgen with the large ionization chamber, marked by *B* in the figure.

Such an instrument, indeed, should be considered an indispensable component of the x-ray equipment, since it lends itself to guarding the x-ray personnel against the cumulative effects of the disseminated x-radiations. It offers a true *quantitative measurement* of the stray radiation dose.

(d) *X-Ray Screening Powers of Different Materials.*—In planning for building a new x-ray laboratory where a high-tension equipment is to be installed, it is of vital importance that special consideration be made for adequate protection of the personnel and the radiographic films against disseminated x-radiations in the room. This protection may be assured by shielding the x-ray tube with x-ray insulating materials and further providing the operator with appropriate ray-proof aprons, gloves, screens, etc. Of these materials, lead offers a most effective screening, but because of other limitations, its application exclusively in all types of x-ray insulation has found demand only with reservation. The fact remains that it is more convenient, in certain types of x-ray screening (as in tubes with built-in x-ray protection, etc.) to use a mixture of lead compound, or a lead-impregnated material, to ensure an effective x-ray protection.

For x-ray shielding, the use of sheets of lead in lining the protective screens, the walls and floor coverings of the x-ray laboratory, and the film storage cabinet, is still a common practice. But, where desirable, the walls and the floor of the x-ray room may be built with ray-proof materials other than lead itself. When employing such a material its protective power relative to lead must be taken into consideration. For instance, barium plaster affords a protection of approximately 1/10th of that offered by lead of the same thickness. Therefore, the walls of the x-ray room may be plastered with a layer of this mixture of a thickness between 8 to 10 times that of lead necessary to provide adequate x-ray protection. In the case of brick or concrete walls, approximately 100 times the equivalent lead thickness is required to ensure the same protection. Kaye and Owen have determined the lead equivalent powers of some protective materials, which are included in Table V. It will be noted that the comparison of the different materials is made relative to 1 mm of sheet lead, and the source of x-rays is assumed as one

from a Coolidge x-ray tube energized by a tension of 100 kilovolts and producing limiting wavelengths of the order of 0.12 angstrom.

TABLE V:—LEAD EQUIVALENT SCREENING POWERS OF MATERIALS

Material	Protective Power
Lead	1.00
Lead Rubber	0.25 - 0.45
Lead Glass	0.12 - 0.20
Bricks and Concrete	0.01
Woods.....	0.001
Barium Sulphate Plaster*	0.05 - 0.13
Steel.....	0.15
Brass ¹	0.25
Aluminum ²	0.016

By use of equation (65), the x-ray protective power of any element may be calculated by first determining its thickness which will produce an equal diminution of the x-ray intensity as that obtained by employing 1 mm of lead at the same distance from the radiation source. It must be kept well in mind that the lead-equivalent relations of the different substances are constant and independent of the voltage applied to the tube.

The safety recommendations, as regards the minimum equivalent thickness of lead for adequate protection for various high-

TABLE VI:—MINIMUM EQUIVALENT OF LEAD VS. VOLTAGE

X-Rays Generated by Voltages Not in Excess of	Minimum Equivalent Thickness of Lead (mm)
53 Kv or 75 Kv.P.	1.0
70 Kv or 100 Kv.P.	1.5
88 Kv or 125 Kv.P.	2.0
100 Kv or 150 Kv.P.	2.5
125 Kv or 175 Kv.P.	3.0
140 Kv or 200 Kv.P.	4.0
160 Kv or 225 Kv.P.	5.0
210 Kv or 300 Kv.P.	9.0
280 Kv or 400 Kv.P.	15.0
350 Kv or 500 Kv.P.	22.0
425 Kv or 600 Kv.P.	34.0
560 Kv or 800 Kv.P. ¹	65.0
700 Kv or 1000 Kv.P. ²	90.0

*This mixture contains 3 parts BaSO₄ and 1 part Portland Cement.

^{1, 2} Author's Insertion.

tension voltages, adopted by the International X-Ray and Protection Committee as in record in the National Bureau of Standards Handbook 15, and HB20, specify various minimum lead-equivalent thicknesses, shown in Table VI, as adequate shielding against radiations incited by given tube tensions.

The Tables V and VI in conjunction with the use of equation (65) will prove of great assistance in arriving at a solution regarding complete x-ray protection in matters of design and construction for an adequately equipped x-ray laboratory. The different materials included in Table V are suggestive of their adaptability to the particular type of building structure, x-ray machine, exposure hood, film storage bin, etc., in the providing of an absolute ray-shielding.

(e) *Sanitation; and, Medical Examination for X-Ray Operators.*—The American X-Ray and Protection Committee in cooperation with the International Congress of Radiology has adopted a series of safety recommendations and unified protective measures to improve the working conditions of x-ray practitioners. A copy of the pamphlet form may be secured from the Superintendent of Documents, Bureau of Standards, Washington, D.C. It is suggested that every x-ray operator should be familiar with the content of the document, and that current revisions on safety recommendations published after each Congress should be preserved for reference.

Some of the essential conditions to be observed for the health and safety of the x-ray worker is to provide the x-ray department not lower than ground level. Adequate exhaust ventilation for all rooms, including the processing room, should be provided to remove all deleterious gases. Further facilities should be had for effective lighting, and, where possible, for admitting sunshine and circulating fresh air into the room, which must be of liberal dimensions. In case natural ventilation cannot be obtained under the conditions prevailing, artificial circulation of the air should be supplied (at the rate of 25 to 40 cubic feet per minute) by motor-driven fan units. A most modern and effective method of providing adequate ventilation and humidity, and of maintaining a constant temperature (about 65°F.) of the x-ray room is an air-conditioning unit obtainable from Gen-

eral Electric, Westinghouse, and many other electrical supply dealers.

A high-voltage roentgen generating apparatus for heavy industrial work should be placed in an adjoining room and the current led into the x-ray tube through heavily insulated flexible cables. The procedure minimizes all risks of contact with high voltage, corona discharges, etc., thus aiding the effective promotion of health and safety conditions of the x-ray worker.

It has already been pointed out that susceptibility to cumulative effect of small x-ray doses is an impending condition and is dependent upon the loyal cooperation of the x-ray personnel. It is generally known that indiscriminate exposure to the radiation produces in the tissues injuries of chronic character. Of the tissues in the human body, the blood cells and the organs forming them, tissues of the genital organs, and the epidermis exhibit distinct sensitivities to x-rays—the blood cells being more than twice as sensitive as the epidermal cells. Leukopenia (deficiency of white blood corpuscles), anemia (loss of hemoglobin through reduction of red blood cells), cancerous ulcerations, and sterility as a result of x-ray injuries are quite generally known. Data on the subject is mostly procured by observations of the effect produced upon the early investigators unduly exposed to the radiation. Fatal consequences as a result of such exposures have also been reported.

Mention was also made that small daily doses are not harmful to the body, but these must be checked frequently so that the exposure will not exceed the permissible dose.

Since no practical method of efficacious elimination of the disseminated secondary rays has yet been brought to light, the x-ray personnel is constantly subject to the influence of the radiation. It is highly advisable, therefore, that periodic blood corpuscle counts be made of these workers to remove symptoms of excessive exposure, if any, at an early stage. In many of the x-ray laboratories which have gained recognition of the profession, it has become a routine practice to examine the workers once a month or bimonthly for x-ray injuries. The working hours of the staff are, in some institutions, fixed to eight hours per day for not more than six days a week, with a month's vacation preferably during summer months.

If extensive protection against primary rays is provided (which is the case with modern x-ray equipment), it is found that the tendency of an ill effect attendant to the health of the worker is not generally associated with the radiation but is indicative of inadequate ventilation and improper working conditions. Plenty of sunshine, fresh air, and physical exercise will generally obviate the prevalent symptoms.

CHAPTER VI

MAKING A RADIOGRAPH

The immeasurable importance of the role played by industrial radiography in the furtherance of the satisfactory behavior of various materials used in the building of structures of peace-time, or, strategic, character is significantly revealed in a survey of the activities of the various industrial plants participating in the Nation's unprecedented production program.

In the inspection of industrial materials by x-rays there are at least two important points to be considered. First, x-ray inspection is primarily confined to the disclosure of evidence concerning the internal constitution of opaque structural entities by non-destructive methods; and, second, by authentic manifestations secured through use of such procedures the attention of the manufacturer, designing engineer, or the foundry personnel is directed to the potential value of the inspection, aiding him to materially improve the quality of his product and his technique which may have grown through practice by empirical methods.

At present, such an inspection has been found a vital adjunct to the production of all types of military and civilian aircraft, ships, artillery, gun mounts, automotive parts, racks, pressure vessels, welds, hydraulic structures, and a variety of metal fabrications, providing sound performance and securing the safety of human life involved in the operation of such structures.

Owing to the rapid expansion of the facilities of the various industrial plants, the application of x-rays, and gamma-rays from radium, to the inspection of castings, forgings, rolled material, and welds of all types for the purpose of determining the soundness and the homogeneity of structures internal to the fabricated part has become so essential that there is a growing eagerness for the discriminating manufacturer (or the designer!) to radiograph every part that goes into the building of his product. Such a cooperation has resulted in the increased production of technically acceptable material which is sound and dependable from both mechanical and structural standpoints.

1. **Types of Parts X-Rayed.**—The problem of what type of parts should be x-rayed depends on the character of the material and on the method of producing it. At present, it appears that the most important industrial application of x-rays resides in their use for radiographing metal castings, which generally present constitutional uncertainty internal to the metal, owing to a great variety of factors entering into the designing, processing, and founding of the material. Among various other materials that are inspected by x-rays are fabricated metal objects, wheels, hydraulic cylinders, pulleys, vessels, bars, forgings, rolled metals, and welds of all types and character. The examination of such materials are in general confined to the determination of gross defect and to the presence (or absence!) of inhomogeneous structures, disclosing the magnitude, depth, and the angular disposition of such discontinuities.

Flaws, such as gas pockets, internal shrinkage cracks, porosity, inclusions, microstructural irregularities such as metal segregations, and abnormal precipitation of intercrystalline constituents in alloys, all contribute to the failure of the material in service. Indeed, where faithful performance is of vital concern from the standpoint of safety of life which may depend on the mechanical character of the structure, each part should undergo 100% x-ray examination.

Another factor of prime importance is the stress requirements in which the metal under consideration undergoes physical tests. These tests consist of the determination of hardness, tensile strength, elastic limit, yield point, elongation, etc., which only define the soundness of the metal from external and mechanical manifestations, and present little, if any, authentic information as to the true internal structural condition of the metal. The use to which the material is to be applied, and whether or not it is to be machined, and, if so, under what stress conditions, all these singularly or collectively appear to be the deciding factors precedent to the x-ray inspection.

Testing for soundness of steel, bronze, copper, and aluminum forgings, and various metal welds is closely allied to the x-ray examination of castings. Such defects as inclusion of carbon, sulphur, or oxide, and shrinkage pipes and porosity in steel welds, and gas cavities and other imperfections of crystal struc-

tures of the metal are readily detected and diagnosed. This has brought about improvements in the methods of production, and thus has further rendered the general trend for inspection a routine practice.

Radiography has also occupied a prominent realm in the field of plastics, and lately in art. Hard rubber moldings, bakelite frames and panels and cylinders, fiber products, coal derivatives, and woodcraft are x-ray tested for imperfect fabrications and for possible inclusions of foreign matter. In the field of art, the examination has been confined to the determination of genuinity of paintings considered as original. All old paintings (which have been done with inorganic pigments in contrast with organic dyes used in modern paintings) when retouched or tempered in any manner, can be readily detected and imitation work can be discriminated from that of true masterpiece.

Close cooperation with the foundry personnel in an effort to correlate radiographic findings with foundry procedures so that improvements in the design of the mold, gates, and risers may be effected, has lended itself to much success in improving the quality of the casting. This results not only in the curtailment of time and money but also in the improvement of design of bulky parts, reducing dead weight, and increasing usable space so valuable in aerial navigation.

A modern founder has all his first-run or trial production x-rayed 100% both before and after heat treatment until a uniform casting quality has been established. When stabilization of quality is thus attained, subsequent x-ray inspection of the castings varies in accordance with radiographic findings. That is, depending on the type of castings, the use it will be put through, and the ultimate stress requirements under operative conditions, the product is x-rayed from 5% to 100%.

2. Sequence of X-Ray Procedure.—When parts to be radiographed are brought to the x-ray laboratory, they are immediately die-stamped with x-ray identification numbers, and a work order is issued with specific instructions regarding the source of the castings, their destination, and the specific time of delivery required. The parts, then, are placed on mobile carts and carried to an x-ray machine adapted to perform the particular type of operation. That is, materials of greater density and greater thick-

ness require a more powerful machine for adequate penetration by x-rays. For this latter reason, a modern x-ray laboratory is equipped with x-ray apparatus of various voltage ranges, namely from 85 kilovolts to at least 220 kilovolts, with 400 kilovolts being preferable.

With a high capacity x-ray generator recently installed at the Aircraft X-Ray Laboratories, steel objects and hard-to-penetrate beryllium-copper alloys, up to three inches thick, have been successfully radiographed by the author in surprisingly short exposure time. This machine can accommodate parts 2½ feet wide and as large as twenty-five feet long, and is fully x-ray protected and is 100% shockproof. This renders complete security to the operator working long hours at the machine.

A systematic scheme followed in radiographing a metal part will be of decided advantage to the operator. This is particularly important because at times the operator due to an over-confidence in himself and in an attempt to achieve a rapid production does not become aware of his negligence to follow certain little but important rules such as placing on the film a correct serial number, a penetrameter of proper size, a requisition or identification marker, etc., until a number of exposed films are detected as spoiled upon development. Frequently, indeed, this becomes a serious problem in x-ray laboratories.

The correct procedure to be adopted in the radiographing of a part may be summarized as follows:

- (1) Determination of the character of the material and the radiographic views most desirable.
- (2) Die-stamping x-ray identification number on each part to be radiographed.
- (3) Measurement of the thickness of the part.
- (4) Selection of an x-ray machine adapted to render optimum results for work in hand.
- (5) Selection of the finest focal-spot tube if sharpness of definition is desired, the tube at a maximum distance consistent with its load capacity.
- (6) Determination whether or not the use of an intensifying screen, filter, cone, or a Bucky diaphragm is necessary in the exposure.

- (7) Arranging the given view of the part on the film so that all usable space is utilized to a full extent.
- (8) Placing a penetrameter on the casting in accordance with the thickness of the latter, and identifying each casting with a lead numeral corresponding to its x-ray number.
- (9) Correct alignment of the x-ray tube with the principal ray directed perpendicularly to the center of the exposure field.
- (10) Selection of proper exposure factors.
- (11) Lowering the lead-shielded hood over the part to be exposed, and applying the power to make the exposure.
- (12) Removal of the film from the x-ray machine, its proper identification as "exposed," its transfer to the photographic dark-room for processing, and then drying.

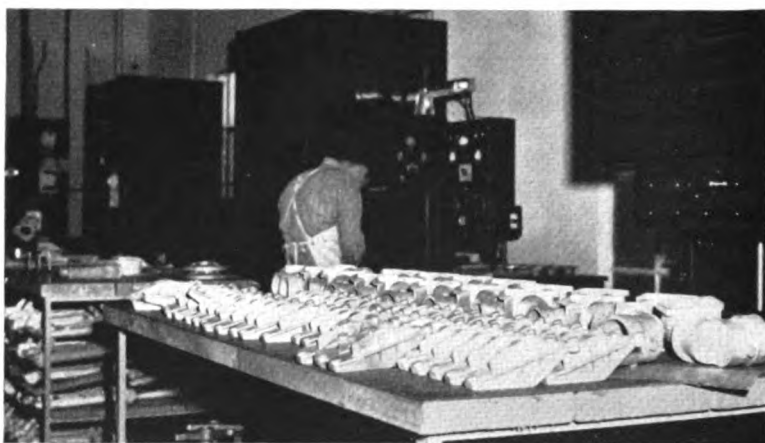


Fig. 60. Each Part To Be X-Rayed Is Die-Stamped With An Identification Number

Upon arrival of the parts at the x-ray laboratory, the first step is to make a requisition form which includes the name of the source of manufacture, the name and address of the firm to which the parts are to be delivered after x-raying, and special instructions to the x-ray operator. The work of the operator then, is to determine the radiographic views which will permit the diagnosis of the part of an optimum degree. These views consist of *straight up-and-down (flat) exposures*, *oblique views*, and *views at right angles* to one view previously taken. This enables the

diagnostician to view the radiograph of the part from almost all angles so that if there be any defect, its exact location, depth, and magnitude may be readily determined precedent to a conclusive report as to acceptance or rejection of the material.

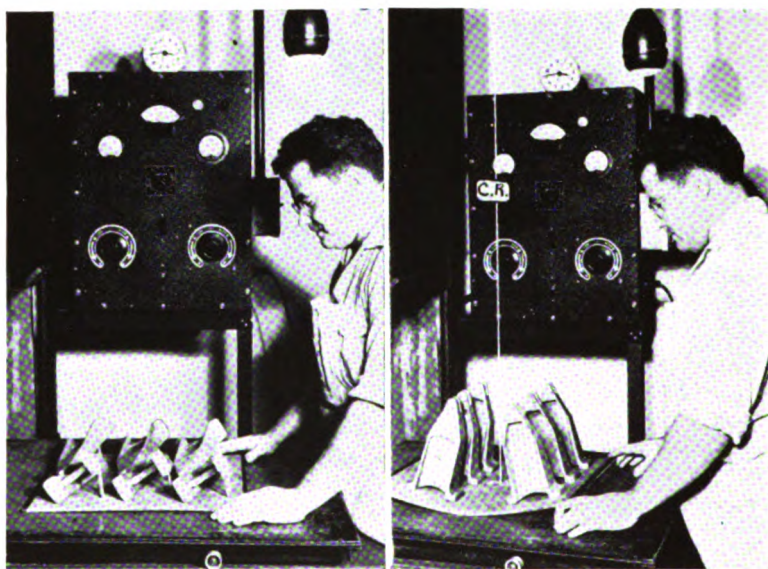


Fig. 61. Measuring the Thickness of the Part to Be Radiographed.

Each part that is x-rayed should be identified with a permanent mark, such as by die-stamping an x-ray serial number on a section of the part which will not be removed during machining of the material. Care should be exercised in selecting the section of the part so that the x-ray number is placed on a thick section and that during stamping no deformation could be effected to that section. This marking becomes a permanent identification of the casting as to its x-ray inspection, and further aids in identifying the casting during diagnosis of the radiograph so that acceptance or rejection of the part can be adequately executed.

Next, measurement of the thickest and the thinnest sections of the part is made, and depending whether the particular exposure is for the thickest section or the thinnest section the radiographic exposure technique is accordingly established. In case it is desired to include, in the examination, the portion between the thickest and the thinnest sections, the exposure factors are set for the thickness of this latter portion. It should be noted that unless the

part under examination is a cube (which is not likely to be so 1 in 100,000 parts) it is expected to obtain a radiograph which has at one section the optimum radiographic density (and hence the optimum interpretable aspects) with sacrifice of contrast in another section or sections. These latter sections, however, are included and revealed in another view (a different angle view on another film). It is then apparent why usually more than one single view is made of a part under examination.



(a) Oblique Alignment of the Parts With Props of Balsa Wood.

(b) Directing the Central Ray to the Center of the Exposure Field.

Fig. 62. Arranging the Parts on the Exposure Holder.

The object to be radiographed, then, is placed on an exposure holder (cardboard film-holder or a cassette) and arranged so that the view exposed offers the most expedient evidence in the examination of the stress regions of the part under consideration. This arrangement may consist of a flat view, or an angle view. Props made of balsa wood (which is very radiotransparent) may be used to support the casting at the angle desired. In routine production, appropriate jigs supporting these castings at an oblique

plane speed up the work considerably. With a little discretion, the operator may acquire the practice of covering all possible areas of the film with castings arranged in regular columns or rows to facilitate the identification of each part during diagnosis. This further saves the manufacturer considerably in radiographic cost of the film.

Having selected the machine which is adapted to render the optimum result for work in hand, and having further determined the character and the thickness of the material, the operator adjusts the kilovoltage to a value for adequate penetration of the part. Since in routine work the milliamperage usually remains constant for all techniques, the time of exposure is set to a convenient value. For instance, for light metals, such as aluminum, magnesium, and their alloys, the milliamperage may be set at *10 M.A.* to *20 M.A.*; for heavy metals, such as copper, steel, bronze, iron, etc., where the potentials are above 220 kilovolts, the current value may be set at *5 M.A.* or slightly over; and, for higher kilovoltage values, such as 800 to 1000 kilovolts, the tube current is usually 2 to $3\frac{1}{2}$ milliamperes for optimum current values.

It should be noted, again, that a discreet x-ray practitioner, usually familiar with the radiographic characteristics of the particular part under exposure, adjusts the kilovoltage to such a value that secondary radiations, if any from that metal, is reduced to a minimum. This may be accomplished, in the case of radiographing heavy metals, by a slight increase (a few kilovolts) in the voltage and a corresponding decrease in the time of exposure. For further methods of eliminating secondary rays, see Sections 6 and 7, Chapter V.

If sharpness of definition is of primary concern, a fine-focus x-ray tube should be selected, since *the smaller the effective focus the sharper the detail obtained*, and hence increased diagnostic quality of the radiograph. If the shift from one x-ray tube to another cannot be conveniently accomplished (as routine production calls for stationary and fixed x-ray tube), where possible, the x-ray tube having the large focus may be moved up to a greater distance (for instance, from 36 inches to 48 or 54 inches, or even to 72 inches). This simulates the effect of a smaller effective focus, and therefore, the resulting radiograph will possess qualities similar

to that taken with a fine-focus tube. In changing the tube-film distance, however, proper consideration must be given to the permissible tube capacity, as an increase in distance will necessitate an increase in tube load consistent with tube capacity.

One of the important factors requisite to the attainment of a sharp, true image of a part radiographed is the correct alignment of the area of interest in respect with the focal spot and the recording surface (film). The *principal ray*, which is assumed as a very narrow pencil of beam projecting from the target at right angle to the long axis of the x-ray tube and is of the least diver-

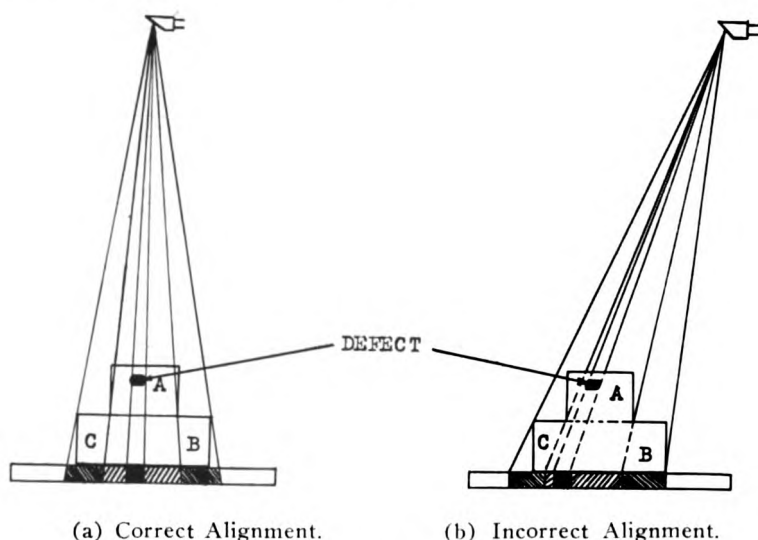


Fig. 63. Aligning the Part With Respect to the Principal Ray and Exposure Field.

gent character, *should be directed perpendicularly to the center of the exposure field* of the part and that of the film. In doing so, close approximation of the part to the film is very essential. If this is not possible, due to the interposition of a lead-grid Bucky diaphragm between the film and the part radiographed, or due to the particular angulation of the part with respect to the film surface, the target-film distance may be increased so as to offset the tendency for the structures remotest from the recording surface from becoming superfluously enlarged.

When the above conditions are fulfilled, the resulting radiograph will be free from false distortion (twisting or deformation of the image due to incorrect angulation of the part with respect to the target and the film planes), and the true shapes and the outlines of the structures under examination will be conserved. To further illustrate this effect, Fig. 63 represents the aligning of a part with respect to the principal ray and the film. In (a), the part to be radiographed is in correct relation to the principal ray and the exposure film, the thickness of the latter having been

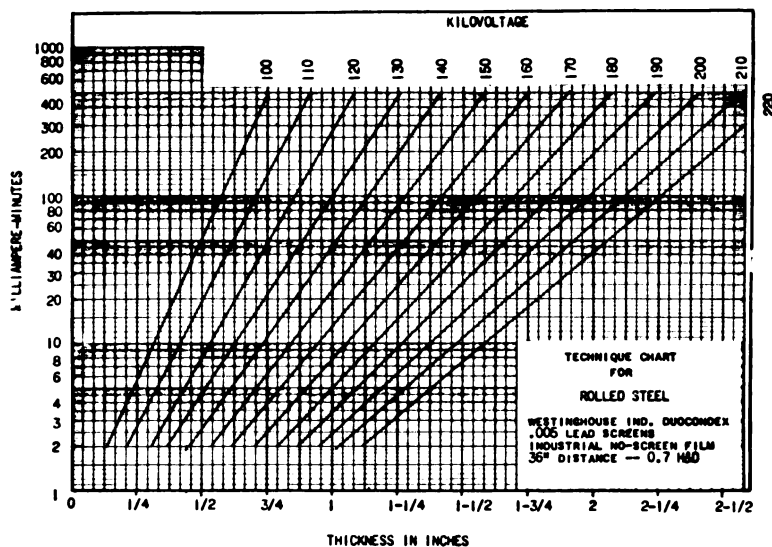


Fig. 64. Exposure Chart For Steel.

greatly exaggerated for sake of illustration. The image in this radiograph will be slightly enlarged in proportion to the thickness of the part under exposure and to the target-part distance. (All radiographs, without exception, present slight magnification!)

On the other hand, in Fig. 63b, in which the principal ray is directed out of the center of the area to be radiographed, it will be noted that the radiographic image of the section *A* is elongated with a portion of section *C* superimposed on it, while the image of the section marked *B* is slightly foreshortened and is overlapping a part of section *C*. The radiograph resulting from such

positioning will not reveal the true interpretable features of the image, since no correlation between the possible defect and the relative contiguous portions can be made accurately so as to consider the radiographic interpretation conclusive.

It becomes obvious, then, that if the attainment of a radiograph with the most diagnostic characteristic is sought, the alignment of

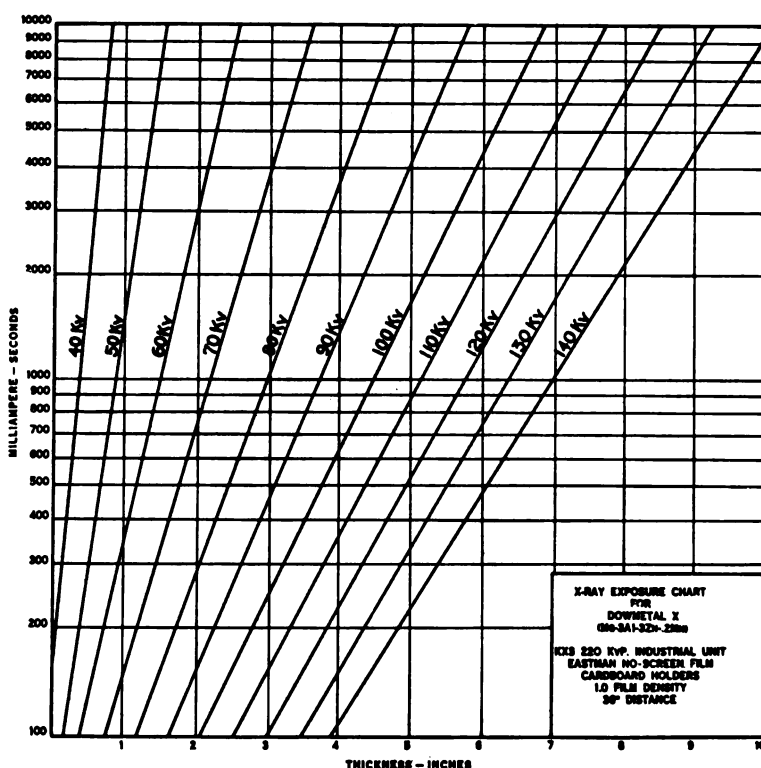


Fig. 65. Exposure Chart For Magnesium.

the part in correct relation to the principal x-ray beam is of primary importance. To accomplish this, the principal ray should fall (as nearly as is practicable) on the center of the area of radiographic interest and to the center of the exposure field of the film. If several castings are to be radiographed on one film, the principal ray will be incident only on the one arranged at the center of the exposure field. In such an event (which is very

TABLE VII:—DENSITY OF MATERIALS, AND THEIR EQUIVALENT THICKNESSES RELATIVE TO 1-INCH STEEL.

Material	Density Gm/Cc	Steel Equivalent	Steel Factor
Aluminum 195	2.77	0.35	2.38
Aluminum 220	2.55	0.32	3.08
Aluminum 356	2.63	0.33	3.00
Aluminum Bronze	7.60	0.97	1.03
Brass (red)	8.60	1.10	0.91
Copper (Pure)	8.90	1.13	0.88
Copper-Beryllium	8.23	1.05	0.95
Gold (pure)	17.17	2.18	0.45
Iron, Wrought	7.85	1.00	1.00
Lead (pure)	11.34	1.44	0.70
Magnesium Alloy	1.83	0.23	4.26
Monel	8.90	1.13	0.88
Phosphor Bronze	9.00	1.15	0.87
Platinum	21.37	2.72	0.37
Steel	7.85	1.00	1.00
Steel (silicon)	7.60	0.95	1.03
Tungsten (pure)	18.90	2.40	0.41
Tungsten Carbide	14.00	1.80	0.56
Tin (pure)	7.29	0.94	1.07
Zinc Alloy	6.7—6.8	0.85	1.17

$$\text{Steel Equivalent} = \frac{\text{Density of Material}}{\text{Density of Steel}}; \text{ Steel Factor} = \frac{\text{Density of Steel}}{\text{Density of Material}}$$

common), the ends of the exposure holder may be slightly lifted by props to conform to the arc of the primary radiation projection. See Fig. 62b.

Subsequent to determining the *character* and the *thickness* of the material under examination, the *target-film distance*, and the

type of film to be used, the radiographic exposure factors are accordingly established and the controls on the x-ray panel are adjusted for these factors. The accurate determination of the exposure factors is very important, as the quality of the resultant radiograph is directly dependent upon the authenticity of this pro-

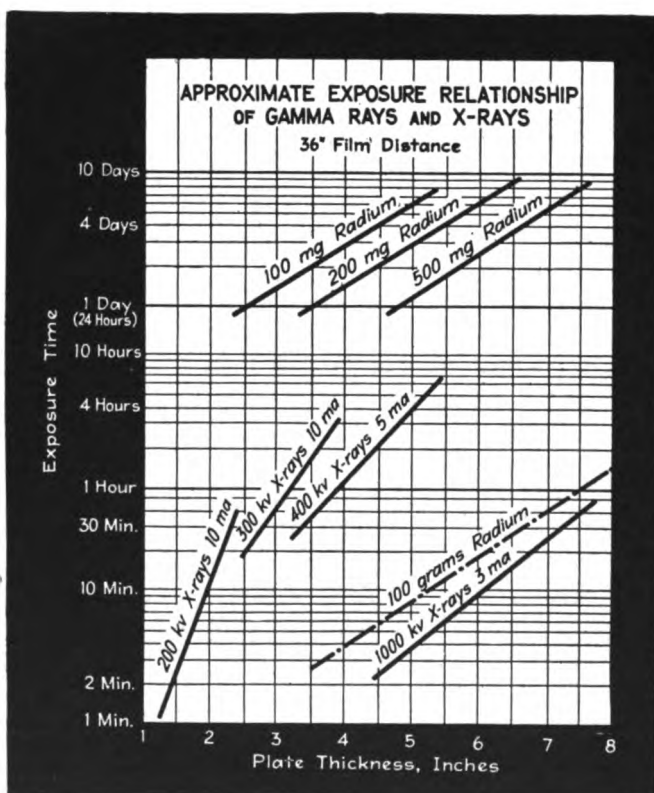


Fig. 66. Exposure Chart of X-Rays and Gamma-Rays.

cedure. An x-ray practitioner generally has available charts and graphs showing the various exposure techniques that may be employed on various types of metals, and on various thicknesses for a given metal. In case such information is not available, the technician can establish his own exposure factors by consulting the charts such as shown in Fig. 64, or 65, Table VII, and equation (68).

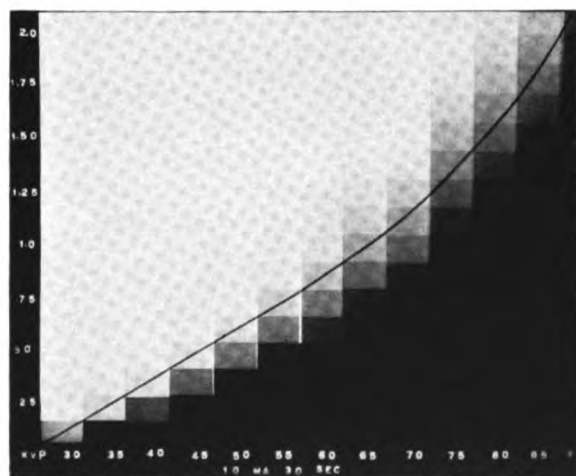
In the further event that the x-ray operator does not possess any information, charts, graphs, or tables giving any form of exposure instructions, he may resort to charting a graph from data obtained by a step-ladder radiograph made on the machine under consideration. Such data may be obtained by radiographing the ladder of the given metal at constant milliamperage and exposure time by only varying the kilovoltage for each exposure. Then, selecting identical densities from each ladder made at different kilovoltages and plotting a curve with the kilovoltage against the thickness of the material, a reasonably accurate curve approximating a straight line can be obtained. Such a curve may also be produced for the exposure time by retaining the kilovoltage and the milliamperage constant and by following the same procedure as for the kilovoltage, with the exception that the time of exposure is varied instead of the kilovoltage.

In Fig. 67a is shown a radiograph of an aluminum ladder. The kilovoltage of each ladder is given under the illustration, whereas the various thicknesses are shown in the vertical column. A curve is drawn to indicate the steps of identical density. It should be noted that this curve is almost a straight line and that its slope is in conformity with the graph shown in Fig. 67b, which graph is made by plotting the various thicknesses of the ladder against the kilovoltages producing the same radiographic density. The series of radiographs is of the same aluminum ladder taken with different exposures set for the different values of the applied potential, with the milliamperage and the time of exposure having been kept constant. The aluminum ladder has 16 steps, each varying $1/8$ th inch in thickness from the preceding one, the lowest step having a thickness of $1/8$ inch, and the thickest portion being 2 inches thick.

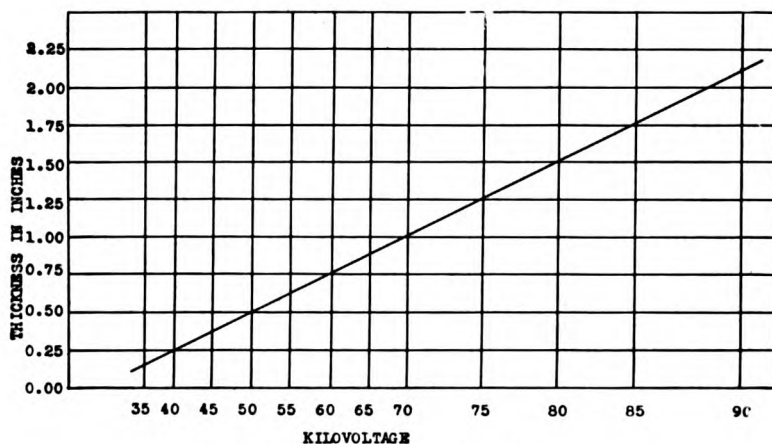
As will be noted, the radiograph made of the thinnest section has the greatest density while that of the thickest section has the smallest radiographic density, and hence the attenuated density at this latter section of the radiograph. The effect is in conformity to our previous assertion that the intensity of the emergent x-rays is dependent upon the thickness of the material traversed.

It will be further observed that each one of the respective 16 steps through which the curve is drawn has the same density, in-

dicating that the area of each of these steps received an equal distribution of x-ray energy, whose absorption by the emulsion of the film is a function of the wavelengths of the radiation. This is indicative that the various beams of x-ray radiations reaching these selected areas have approximately the same *spectral distribution*, even though the wavelengths of the radiation producing the



(a) Radiograph of Aluminum Ladder.



(b) Graph Plotted from Ladder Shown in (a).

Fig. 67. Radiographs of an Aluminum Step Ladder Taken With Various Kilovoltages.

various selected step areas were not identical in view of the different voltages employed in the different ladder radiographs.

Because of the differences in the characteristics of the different films, the differences of the processing materials and the processing conditions from one time to another (and from one laboratory to another!), the establishment of a standard has not been adequately set forth. But, considering that on the whole one established technique of one laboratory differs, if any, from that of another to an extent of what quality radiograph one laboratory deems to be more satisfactory as regards accurate diagnosis appears to be a matter of opinion and falls short of prime importance. Standardized chemicals, maintenance of a correct temperature of the processing solutions, and the time of development, however, will aid to a considerable extent in the attainment of radiographs of optimum quality.

When an accurate exposure technique is established for a given type and thickness of the material, exposure factors for other materials of the same thickness may be calculated by use of equation (68), which involves a comparison of densities of any two metals one of which has an established exposure technique. For instance, let us assume that it takes 1.5 minutes at 180 Kv.P. , and 10 M.A. to radiograph a certain piece of steel $1\frac{1}{4}$ inches thick at a focus-film distance of 36 inches. How long will it take to radiograph phosphor bronze having the same thickness, all other factors remaining same?

First, using equation (68) we calculate the steel equivalent thickness of phosphor bronze as 1.437 inches. By consulting the chart for steel, Fig. 64, we find for 1.437 inches of steel radiographed at 180 Kv.P. an exposure factor of 35 milliampereminutes. At 10 milliamperes, this exposure time for 1.437 inches of steel (equal to 1.25 inches of bronze) will be 3.5 minutes, which is the time of exposure for 1.25 inches of phosphor bronze at 180 Kv.P.

Having selected the correct exposure factors and further having adjusted the controls to proper settings, the parts (which are arranged on the exposure holder lying over the platform on rollers) are rolled into the machine (See: Plate I) and the hood is lowered so as to exclude the dissemination of x-radiations from the operator. The exposure push-button is pressed, which pro-

cedure energizes the x-ray tube, and the exposure is made. The automatic timer mechanism opens the circuit after the set exposure time has elapsed. In some x-ray machines, there is a safety switch mounted inside the door of the hood so that it is impossible to energize the x-ray tube unless the hood is completely closed. This offers an added safety factor from the standpoint of x-ray protection.

Next, the hood is raised, the mobile platform is pulled out, and the castings are placed on shelves adequately marked for later identification of the parts. The exposure holder of the exposed film is properly identified by means of adhesive tape, or by means of a square cardboard or paper inserted between the folds of the holder so that a portion of the paper projects from the outer margin of the holder. When the entire lot of the castings is radiographed, the films are transferred on mobile carts into the processing room where they are developed, fixed, washed, and dried (in a modern x-ray laboratory) on automatic motor-driven conveyors moving through a blast of warm air at a temperature of 90 to 98° F. The dry films are ejected at the other end of the drier cabinet into the film write-up room, where the films are arranged with their x-ray serial numbers in consecutive progression. The radiographs are then ready for diagnosis.

3. Radiography of Welds, and Irregular Structures.—

Because of the great improvements and advances in welding machinery and technique made within last decade, many structures in ships, aircraft fuselage joints, bridges, high pressure vessels, and other assembly parts are joined together by welding. At present, welding has replaced, in majority of constructional work, the time-consuming process of riveting.

In welding, two metals are united usually by fusion at high temperature. The union thus produced, if executed properly, is often much stronger than the base metals entering into the joint structure. But frequently welded joints may appear on the surface to be perfectly sound, yet in the interior of the metal there may exist a lack of homogeneity or fusion due to improper heating of the metals to be joined, to inclusions of slag, to an excessive accumulation of oxides or porosity from evolution of gas during the process of welding, and due to shrinkage cracks occurring either during welding or subsequently.

Therefore, a radiographic inspection of welded parts not only removes all uncertainties regarding the quality of the weld struc-

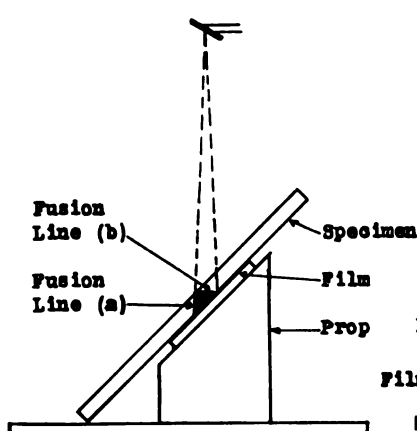


Fig. 67. A Butt Weld With Bevel at 45° Angle. A Second Exposure May Be Made at Right Angles to Show Fusion Line (b).

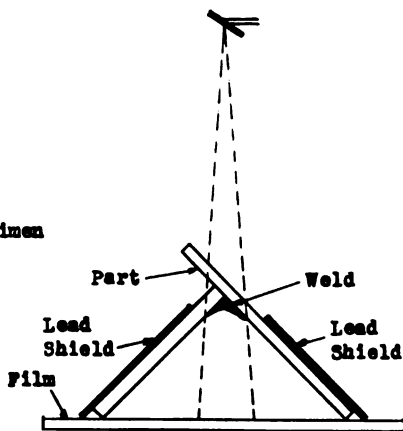


Fig. 68. Arranging the Film For Fillet Weld Exposure. Field Outside of Weld Is Shielded to Prevent Scattered Radiation.

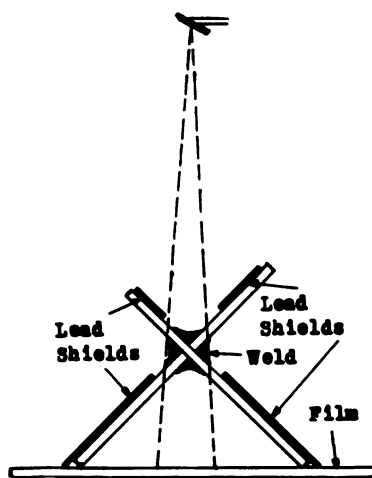


Fig. 69. Manner of Radiographing a Cross Weld. Note Various Lead Shieldings.

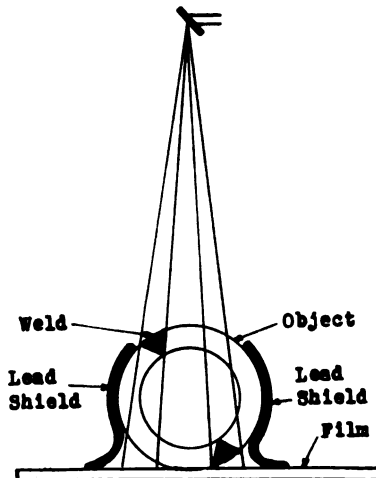


Fig. 70. Longitudinal Weld in a Cylinder or Tubing.

ture but also actually assures the serviceability of the structure, and is a money-saving practice to the manufacturer concerned

There are various types of welds and welding processes, which

are too numerous for detailed discussion in this writing. Therefore, a few of the most common welds which will permit the illustration of the technique of radiographic inspection are given in the foregoing figures. The manner of arranging the part in respect to the x-ray beam and the film is presented briefly under each illustration.

Irregular structures, especially of metals of high atomic weights, such as iron casting, steel, bronze, and the like, may be satisfactorily radiographed if adequate shielding is provided. For in-

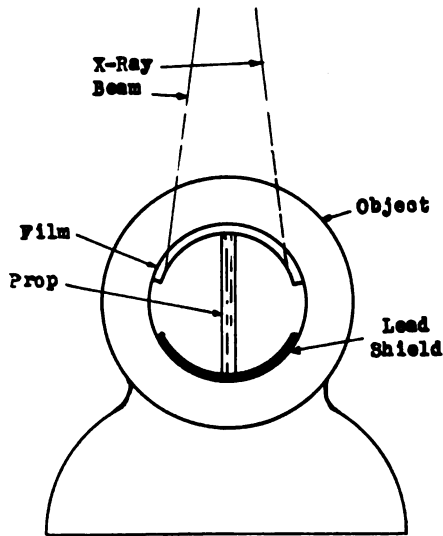


Fig. 71. Radiographing the Cylinder Body of a Cast Iron Safety-Valve.

stance, all parts of the object outside of the center of interest and exposed to the radiation may be shielded by suitable sheets of lead covering these regions at points nearest to the x-ray tube, as shown in Figs. 67 to 70. If this cannot be practicably arranged due to various gradations of thicknesses which are to be radiographed, copper shots or copper powder may be placed directly over the thinner sections in amounts sufficiently large to enhance the proper radiographic density for adequate detail visibility and accurate diagnosis. Figures 71 and 72 illustrate the important phases of the general scope of the discussion.

It should be noted with reference to Fig. 72 that the quantity of copper powder required to compensate for the radiographic density produced by the cylinder wall of the object is determined by calculating the equivalent height of the copper powder above the flange. This may be accomplished, if the density of

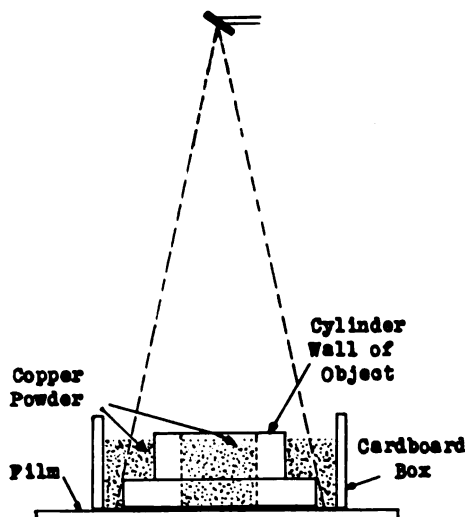


Fig. 72. Steel Structure Shielded With Copper Powder to Equalize the Radiographic Density.

the copper powder is known, by placing on the flange a quantity sufficient to equal the equivalent height of the cylinder wall above the flange as shown in the figure. Filling the inside of the cylinder to the same level with the powder (or shots) will prevent an excessive blackening of the film at this point, and particularly will eliminate restrained development, erroneously called in general as "*film bleeding*."

4. Radiographic Exposure Factors.—It has been already observed that the quantity of x-rays produced in an x-ray tube is dependent upon the milliamperage through the tube, the impressed voltage, and on the target material. It is also noted that the radiation output of a given x-ray tube having tungsten for its target varies directly (with certain limitations) as the square of the voltage applied to the tube. Two tubes (electron type)

of essentially the same electrical and mechanical characteristics should, therefore, produce the same x-ray output under identical voltage and current conditions. This is not, however, strictly true in common practice, in the sense that two such identical x-ray tubes are not usually operated on the same machine and under the same conditions. Whether the tube is connected on a mechanically rectified machine, or on a half-wave, or full-wave, valve-tube rectification system, and whether the target is air-cooled or water-cooled, all introduce minor differences in the tube load, and therefore have bearing on the radiation output of the x-ray tube. For all practical purposes, however, it will not be infeasible to expect the same efficiency from two different x-ray tubes of the same make, type, rating, and mechanical construction, as the manufacturers of x-ray tubes are constantly improving the design, the character of electron acceleration and focusing on the target, and the accuracy of the assembly of the various parts of their tubes.

In considering two x-ray tubes of different inherent characteristics, variation in output, which indeed is occasionally observed, may be due to the differences in the design and hence increased stem radiation in one tube with respect to the other, warping or pitting of the target of one tube or the other, differences in target angles, spacing between the cathode and the anode, magnitude of tube bias, the character of the target cooling system, and variations in the nature and the thickness of the glass envelope.

We shall, therefore, confine our discussion in the accompanying sections to the radiation from any given x-ray tube, irrespective of its mechanical and physical characteristics. An attempt to generalize the applications of radiation-limiting devices or objects external to the x-ray tube and of the controlling electrical factors will be made from routine radiographic production standpoint.

The quantity of x-radiation absorbed by the sensitized emulsion of a radiographic film determines the *radiographic density* of the image. The radiographic density is defined as the degree of blackening produced in the film by the incident x-radiation. More technically speaking, the term may be expressed in an

equation form as

$$D = \text{Log } \frac{I_o}{I} \quad (83)$$

where, I_o is the intensity of the x-radiation incident upon the film, I is the emergent radiation intensity, and D is the density of the image formed in the radiograph.

While the production of the x-emission from the x-ray tube varies directly as the square of the applied voltage, the absorption of the radiation by the emulsion of the film varies inversely as the cube of the voltage and directly as the cube of the wavelength of the incident ray. Furthermore, the interposition of the object to be radiographed and the radiation-limiting devices such as filters, diaphragms, etc., further impose limitations on the quality of the x-rays affecting the film emulsion.

Some of the essential factors which influence the x-ray output and the intensity of the radiation reaching the radiosensitive emulsion of the film may be summarized as follows:

- (1) The milliamperage and the impressed kilovoltage.
- (2) The atomic number of the focal spot material.
- (3) The penetration quality of the resultant x-rays from (1) and (2).
- (4) The focus-film distance.
- (5) The thickness and the density of the object radiographed.
- (6) Use of filter, cone, or diaphragm in the exposure.
- (7) Use of exposure holders—intensifying screens (double or single), or cardboard exposure holder.
- (8) The duration of the exposure time.

Of the above variable factors, those that are controllable by the x-ray machine are the impressed voltage, milliamperage through the x-ray tube, focus-film distance, and the duration of the exposure. An equation expressing the relative interdependence of these variables may be formulated as

$$I_o = \frac{Kv.P^x \times M.A. \times T}{D^2} \quad (84)$$

in which, I_o is the intensity of the primary x-rays as they become incident on the object (also known as the radiographic energy), T is the time of exposure in seconds, and D is the focus-

film distance usually given in inches or in centimeters. The superscript " x " of the quantity $Kv.P.$ is variable, and for moderate voltages it may be taken as having a value 2.

Let us assume that with a certain exposure technique using 60 $Kv.P.$, 10 milliamperes, and an exposure time of 8 seconds at a focus-film distance of 36 inches, a proper radiographic density is obtained. But, owing to the high magnitude of distortion (magnification) prevalent in the radiograph due to small focus-film distance for that particular object, the distance is changed to 54 inches. This change, of necessity, entails a corresponding increase in the time of exposure. The question is, "How much should the time of exposure be increased?"

The problem gives the values constituting the radiographic energy I_1 for the first technique, and all the values of the variable quantities, except the time of exposure, of the second technique. In order that the same degree of radiographic density is obtained in the second technique as that in the first, the radiographic energy distribution of technique 2 affecting the film should be equal to that of energy reaching the film of technique 1. Hence, equating the radiographic intensity I_1 of technique 1 with the radiographic intensity I_2 of technique 2, and substituting the numerical values given for the two techniques, we solve for the unknown exposure time T_2 of technique 2. Thus, we have

$$\frac{(60)^x \times 10 \times 8}{(36)^2} = \frac{(60)^x \times 10 \times T_2}{(54)^2}$$

Cancelling the equal quantities from both sides of the above equation, and equating for T_2 , we obtain

$$T_2 = \frac{(54)^2 \times 8}{(36)^2} = 18 \text{ seconds. } Ans.$$

Owing to the divergent character of a beam of x-rays as in visible light originating from a point source, it will be noted that the intensity of x-radiation decreases as the distance from the focal spot of the x-ray tube is increased. In Fig. 73, it is assumed that a constant x-ray emission is maintained from the target A of a given x-ray tube. When the beam is allowed to become perpendicularly incident upon a radio-opaque object P , such as a

sheet of lead, the latter will cast a shadow in accordance to its relative position between the target and the shadow-receiving surface S , which may be a fluorescent screen or a radiographic film. It is further assumed that P has an area of 4 square inches and is placed 20 inches from the target A . The screen S is placed parallel to P with their centers perpendicular to each other, the distance between A and S being 40 inches.

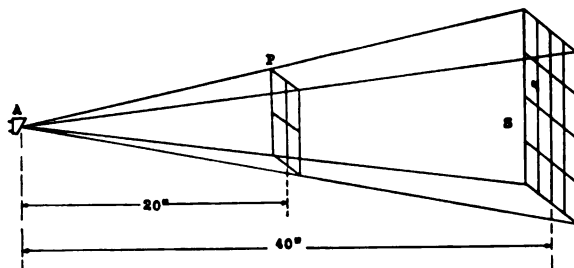


Fig. 73. Divergence of an X-Ray Beam.

Since the object P is midway between the source A of the radiation and the fluorescent screen S , it is by no means in close relation with the surface of the latter. Hence, the image thus formed will be magnified. More precisely, the area of the image of P on the screen S will be four times as large, as clearly illustrated in the figure. That is, the area of the image of P formed on the screen will be 16 square inches.

From the above illustration it becomes obvious then that the intensity of x-rays covering the area P will be four times greater than the intensity of the radiation reaching the screen S when P is removed, as the same amount of the radiation covering 4 square inches at P is distributed over an area of 16 square inches. Therefore, each square inch of the screen area will receive an x-ray intensity $1/4$ th that of each square inch of the area of P . It will be further noted that doubling the distance where the intensity is observed will reduce the x-ray intensity to $1/4$; and, similarly, tripling this distance will decrease the intensity to $1/9$, and so forth, of the original intensity measured at the first given distance. Conversely, halving the target-screen (or, focus-film) distance will quadruple the intensity of the x-radiation at the receiving surface. This relation, known as the *Inverse Square Law*, states that the intensity of x-rays varies inversely as the square of

the focus-film distance. It may be represented in an equation form as

$$I = \frac{1}{D^2} \quad (85)$$

where I stands for the intensity in terms of the arbitrary unit 1, and D is the distance between the source of radiation and the radiation-receiving surface.

Let us consider a radiographic film placed at P and exposed to the radiation for 3 seconds. If the resultant density is assumed to be optimum quality, then, if a film is placed at S , which is twice the distance from the target A , namely 40 inches, and, therefore, receives 1/4th the intensity as at P , which is 20 inches from the target, the time of exposure for this second film must be prolonged 4 times in order that the same radiographic density as at P may be realized at S . That is, the exposure time for the second film at 40 inches from the target will be $3 \times 4 = 12$ seconds.

Putting this relation in the form of a rule, we have: *The intensity of x-ray radiation varies inversely as the square of the focus-film distance; hence, the exposure time is directly proportional to the square of the distance.*

The equation of this rule may be expressed as

$$T_2 = \frac{T_1 D_2^2}{D_1^2} \quad (86)$$

in which, T_2 and D_2 are respectively the exposure time and the focus-film distance of the new technique, and T_1 and D_1 respectively stand for the exposure time and the focus-film distance of the original technique, whose factorial values should be known.

Some x-ray practitioners prefer to express their exposure techniques in terms of milliamper-second factor (written *Ma-S*). This is permissible when optimum penetration has been secured by proper kilovoltage for the given thickness of the material. The milliamper-second factor, when other factors are constant, will increase or decrease the density and hence the contrast of the radiograph. On the other hand, other practitioners find it to their advantage to keep the *Ma-S* constant for a given type of material and to change the kilovoltage in accordance with the various

thicknesses to be penetrated. It appears, however, that general practice favors the change of the various exposure factors according to the problem in hand.

When the kilovoltage is adjusted with reference to the focus-film distance and to the thickness of the part under consideration, the exposure time, or, the milliamperage, may be varied by the relation given as follows:

$$Ma_1 \times T_1 = Ma_2 \times T_2 \quad (87)$$

$$T_2 = \frac{Ma_1 \times T_1}{Ma_2} \quad (88)$$

where Ma_1 and T_1 are respectively the milliamperage and the time of exposure (in seconds) of the first technique, and Ma_2 and T_2 are the respective quantities for the second technique.

Frequently it is particularly desirable to reduce the *distortion* (magnification) of the radiographic image to a minimum, as when the part to be radiographed is very thick the image of the portion remotest from the film will be greatly magnified. This is usually accomplished by increasing the focus-film distance and by correspondingly raising either the kilovoltage, or, the milliamperage, to compensate for the change. If the latter condition is met, we have the relation

$$\frac{Ma_1}{D_1^2} = \frac{Ma_2}{D_2^2} \quad (89)$$

in which, D_1 and D_2 are respectively the focus-film distances of the first and the second exposure techniques.

In radiographing thick parts, it will be found very expedient to increase the focus-film distance to a maximum consistent with the x-ray tube capacity, since at an increased distance the rays projecting from the target will have less divergent character and hence the resultant image will be magnified to a smaller degree.

The practice of controlling the scale of gradation of a radiographic density by proper selection of the impressed voltage appears to be favored in the field if the part to be radiographed has a high atomic number. A slightly higher kilovoltage than that given in the usual technique results in the reduction of the milliamperage and the time of exposure, thus minimizing the attendant fogging of the radiograph by the secondary radiations.

When it is desired to make a change in the kilovoltage, the time of exposure may be changed in accordance with the author's figures given in Table VIII, which, for most any practical work is found to be quite convenient to remember and is satisfactory in exposure results.

TABLE VIII:—Kv.P.-TIME-DISTANCE CONVERSION CHART.

Reducing Time by	Increase or Kv.P.	Decrease Distance from	Increasing Time by	Decrease or Increase Kv.P. by	Increase or Decrease Distance by
1/10	2 Kv.P.	72" to 68" 68" to 56" 48" to 45" 36" to 32"	1/10	1 Kv.P.	2"
1/5	4 Kv.P.	72" to 64" 60" to 54" 48" to 43" 36" to 32"	1/5	2 Kv.P.	4"
1/4	5 Kv.P.	72" to 62" 60" to 52" 48" to 42" 36" to 30"	1/4	3 Kv.P.	6"
1/2	10 Kv.P.	72" to 54" 60" to 42" 48" to 36" 36" to 25"	1/2	5 Kv.P.	8"
2/3	13 Kv.P.	72" to 42" 60" to 36" 48" to 27"	2/3	6 Kv.P.	10"
3/4	16 Kv.P.	72" to 36" 60" to 30" 48" to 25"	3/4	8 Kv.P.	14"

Example:—In a certain radiographic technique, exposure factors of 85 Kv.P., 10 milliamperes, and 16 seconds are employed with a target-film distance of 48 inches. It is desired to reduce the time of exposure to 1/2. What change in the exposure factors should occur, if the radiographic density is to be retained constant?

According to Table VIII, either the kilovoltage or the distance may be changed. If the latter is considered, we find in column 3 corresponding to a reduction of 1/2 in the exposure time that the

distance can be reduced from 48 inches to 36 inches to compensate for the reduction in the exposure time.

Supposing that the distance cannot be changed due to the thickness or the shape of the material, and because it is desired to retain the maximum sharpness of the radiographic detail, the potential may be increased by 10 kilovolts, making the exposure factor 95 kilovolts.

5. Intensifying Screens.—As the primary x-ray beam projecting from the tube target traverses the various thicknesses of an object placed in its path and becomes incident upon the emulsion of a radiographic film, it is calculated that only a fraction of this radiation reaching the film is effective in producing the image. This energy amounts to approximately 1% of the incident radiation energy, while the remaining 99% of the energy traverses the film without producing any photographic effect.

Since the degree of blackening of the film is dependent on the amount of absorption of x-rays by the sensitized surface of the film, the 1 per cent radiation energy which is effective in producing various density gradations in the image is naturally insufficient to cause the required blackening in the film emulsion in relatively short exposure times when a thick section of an object is to be radiographed. As was mentioned previously, thick objects require longer exposures, which may run as high as 60 minutes or over, depending on the distance or the kilovoltage employed. Therefore, for such long exposure techniques, a device known as *intensifying screen* may be used to shorten the exposure time considerably.

An intensifying screen consists of a fluorescent material applied to the face of a cardboard plate which is placed in contact with the film emulsion during exposures. The fluorescent chemical absorbs a part of the 99% untransformed x-ray energy and converts it into a visible radiation which in turn exposes the film. The exposure of the film by the direct x-ray radiation plus that from visible rays of the fluorescent screen cause an intense blackening effect on the emulsion when developed. Owing to this characteristic of the fluorescent chemical, the screen on which the material is coated is known as an intensifying screen. The photochemical effect of the combined radiations (x-rays, and fluorescent rays) on the blackening of the film, then, will increase eight to

fifty times, depending on the voltage and on the type of screen used. Consequently, the exposure time by use of intensifying screens will be reduced respectively eight to fifty times in accordance with the type of screen employed.

Certain compounds, such as zinc sulphide, barium platino-cyanide, cadmium tungstate, calcium tungstate, and, infrequently, zinc silicate are used for the fluorescent coating of the intensifying screens. At present, calcium tungstate appears to be universally adopted because of its affording more uniform and consistent radiographic results. The crystalline chemical, after having been ground into a uniformly fine powder, is mixed with a suitable binder, and the resulting mixture is applied evenly on one surface of a sheet of cardboard serving as a support, which is then called an intensifying screen. Two of such screens, in turn, are mounted in a rigid holder, called a *cassette*.

When the cassette is loaded with a film, a uniform contact is established between the two surfaces of the film and the screens on either side. When an object with the cassette placed underneath it is exposed to the radiation from an x-ray tube, the screens become fluorescent and give off a visible light, which blackens the film emulsion, in accordance with the amount of fluorescence determined by the thickness, density, and the shape of the object, and by the duration of the exposure.

If the screens fail to make even contact with the emulsion of the film, the resulting radiograph will be blurred, or the sharpness of detail will be missing, because the fluorescent light of the crystals will spread before reaching the film. A test for determining whether or not the screens are making the proper contact with the film may be performed by placing a wire screen on top of a loaded cassette and making a flash exposure. If even contact is secured between the surfaces of the film and the screens, the image of the wire mesh will be outlined sharply, as shown in Fig. 74. If the image is blurred and the outlines are fuzzy, Fig. 75, poor contact is indicated. When the latter is the case, the screens must be padded with thin paper to eliminate the cause.

Generally an effective screen, such as offered by calcium tungstate, or, fluorazure (zinc sulphide coated with blue organic dye), reduces the exposure time to 1/20th to 1/50th that required for a direct exposure. It should be noted that when intensifying

screens are used, the radiographic image is mainly formed by the fluorescent light, which, being of the same character as visible light, does not traverse opaque bodies such as dust or dirt that may be adhering to the surface of the screen. Such opaque bodies will produce spots or light areas in the radiograph, interfering with the detail of the image. For this latter reason, the screens should be kept thoroughly clean in order that maximum advantage may be realized from them. Dust, or dirt, and smeared

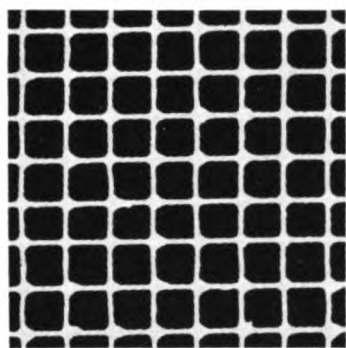


Fig. 74. Sharp Image Due to Proper Screen Contact.

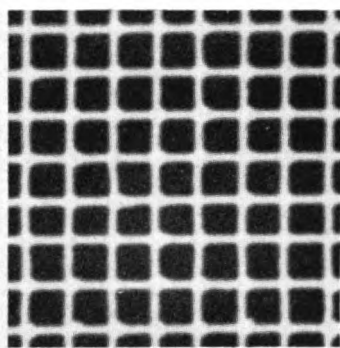


Fig. 75. Fuzzy Image Due to Poor Screen Contact.

markings on the screen from inadvertent handling may be removed by washing it with soap and water, and then by carefully drying with a piece of soft linen. Care should be exercised that the screen surface does not become scratched in so doing.

One of the requisites to modern radiography is the "*speed*" factor, which is affected to a considerable degree by the use of intensifying screens. The speed of the screens may be directly influenced by the *size* of the crystals of the fluorescent material—the larger the crystals the more abundant is the fluorescent light and faster the screen; and, the smaller the crystals the less fluorescent light is given off, and therefore, the slower the screen.

To secure the maximum detail, however, the fluorescent crystals of the screen should be as small and uniform in size as possible. When the latter case is conserved, the sharpness of definition increases with sacrifice in speed. That is, as stated above, the smaller the grain size of the fluorescent crystals the less abundant

is the fluorescence from the screen, and hence the screen speed factor is low and the radiographic definition is high (because there is less diffusion of the fluorescent light before it strikes the film). If large crystals are used in the screen more fluorescent light will reach the film and hence the screen factor will be high (fast screen) but the definition of the radiograph thus produced will be comparatively inferior, as sharpness will be lacking.

An equation expressing the blurring or unsharpness produced by an industrial intensifying screen due to its crystal size is given in the following derivation:

$$U = \frac{f \times d}{D - d} + B \quad (90)$$

in which, U is the total unsharpness or blurring in millimeters, f is the width of the focal spot, d is the part-film distance in inches, D is the focus projection in inches, and B is the blurring or unsharpness factor characteristic of the screen and is given in millimeters. The screen unsharpness factor varies from 0.20 to 0.50, and for industrial screens it is taken as 0.20 mm.

The unsharpness due to an intensifying screen is further elucidated in the illustrations given in Fig. 76, in which the image of a single structural element of an object intercepting the beam of x-rays is projected past a screen and recorded on the film. If a single radiation beam traverses a unit structure A and strikes a large crystal, as in (a), this crystal becomes a source of fluorescent light radiating in all directions. A portion of this light reaches the film at varying angles, and the sensitive emulsion becomes affected wherever the incident light strikes. Only that portion of the fluorescent light that is incident almost normally to the emulsion plane of the film produces an image of sharp detail of the object element, whereas those portions striking the film at angles other than these incidences contribute to the unsharpness of the image.

Owing to the large size of the fluorescent crystal shown in (a), the light from it will cover a larger area than the projected image of the unit structure, whereas in the case of a smaller crystal the divergent fluorescent light will cover only a comparatively small area, as shown in (b). Consequently, the detail of the projected

image will have better definition. Obviously then it will be expedient to assume that the sharpest detail is only possible by the use of crystals of infinitely small size, i.e., by using no crystals. The last is illustrated in (c), in which a cardboard exposure holder is substituted for intensifying screens.

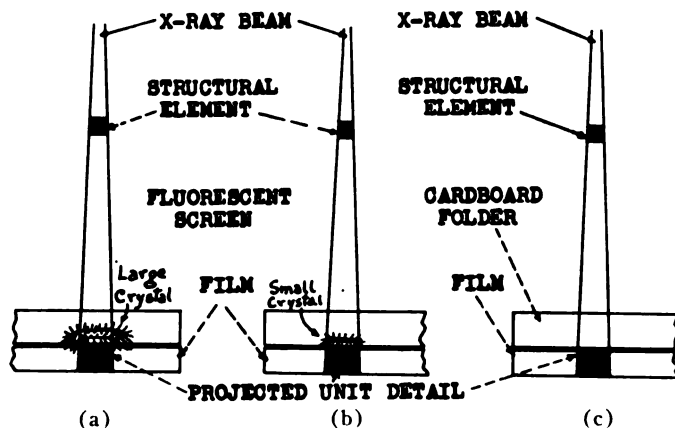


Fig. 76. Comparison of Detail Delineations.

It will be noted that in Fig. 76c the highest quality of image definition is secured. However, the diminished speed by employing no-screen technique will restrict the use of cardboard exposure holders for thick parts in rapid radiography. The intensifying screens, indeed, find great use in the radiography of steel by high voltage or by gamma-radiations even though detail sharpness is sacrificed to a certain extent by employing the screens.

In industrial radiography, various metal foils of thicknesses varying from 0.002 to 0.08 inches are used as intensifying screens. These metals comprise aluminum, zinc, copper, lead, lead-antimony alloy, tin, tin-antimony alloy, zirconium, nickel, etc. Aside from their intensifying properties, they also serve as *filters* for long-wave and undesirable x-radiations. The intensifying factors of these metal foils vary from 2 to 8. Obviously, these screens are much slower than calcium tungstate screens, but the definition obtained by use of a metal foil has very desirable characteristics because of its offering a greater visibility in the diagnosis of the specimen. In using a metal foil screen, however, the kilovoltage

should be slightly increased to compensate for the partial absorption of the radiation by the metal. This absorption of the radiation gives rise to photoelectrons which produce the intensifying action of the metal screen.

With present demand for high speed radiography combined with high definition of detail, one elegant form of intensifying-screen exposure holder will be the *combination of a metal foil screen and a calcium tungstate screen*. Advantage will be had of the filtering properties of the metal foil which may be placed on the upper side of the film, and of the high intensifying quality of the calcium tungstate screen which may be placed underneath the film. The former produces a high definition with the resultant in-

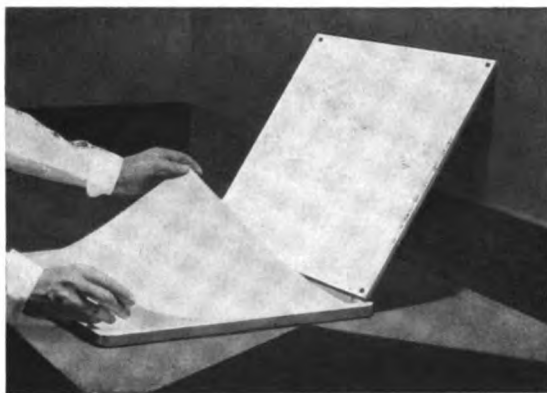


Fig. 77. Loading a Calcium Tungstate Intensifying Screen Holder.

crease in the latitude of the radiographic gradations whereas the latter curtails the usual reduction in the exposure time.

In employing metal foil screens, however, care should be exercised in the selection of the applied voltage. With voltages above 100 kilovolts lead foils or its alloys are found advantageous, while for techniques employing voltages below 100 kilovolts screens of lighter metals of thicknesses specified above may be used.

When intensifying screens are employed in an exposure, the black paper covering of the film should be removed before the latter is inserted into the holder. Fig. 77 illustrates one form of loading an intensifying screen holder (cassette), and in Fig. 78 is shown the manner of loading a cardboard exposure holder. It

should be noted that in the latter case the black covering is left on the film so as to provide an added protection against visible light of any character.

6. Filters, Cone, and Bucky Diaphragm.—Frequently it becomes desirable to obtain the maximum definition in a radiograph by eliminating undesirable x-radiations from the field of exposure. This is accomplished by judicious use of selected metal filters. A filter consists of a thin sheet of metal of uniform thickness and density, and is placed between the x-ray tube target and the object to be radiographed to minimize the effect of the unobstructed radiation which may otherwise cause undue fogging of the



Fig. 78. Manner of Loading a Cardboard Exposure Holder.

radiograph. A preferred method is to place the filter between the upper side of the film and the specimen. The filter at this position will absorb (filter out) extraneous secondary radiations originating in the object and which when incident upon the film will produce undue blurring of the image. The secondary radiation incited by the object being radiographed consists usually of longer wavelengths than those of the primary ray, and, therefore, is absorbed by the filter to a great extent.

In addition to its filtering characteristic, a metal filter of high atomic number usually serves the same purpose as an intensifying screen. Thus, a properly chosen metal filter (placed next to the upper surface of the film emulsion) will serve a dual purpose—eliminating the radiographic fog due to characteristic secondary radiations, and reducing the time of exposure materially owing

to its intensifying properties. However, it must be remembered that the filter of itself will produce secondary radiation, hence due consideration should be directed to the choice of a filter material.

Some of the metals which are generally employed as filters are aluminum, zinc, copper, tin, antimony, lead, lead-antimony, tin-antimony, zirconium, cadmium, and impregnations of any of these metals. The thickness of these filters varies with the character of the filter material and with the type of work for which they are employed. Thin foils of thicknesses varying from 0.002 to 0.08 inch mounted on a stiff cardboard support are usually employed as intensifying screens with the film sandwiched between two such screens with metallic surfaces next to the emulsion of the film. This thickness further varies with the combination of filters that may be used simultaneously. For instance, aluminum is more transparent to soft x-rays whereas copper for harder rays. The combination of proper thickness ratio, therefore, should provide a criterion whereby approximately the same degree of absorption of the medium-hard rays may be realized with applicable feasibility. Such a combination is also possible with tin and lead, zinc and copper, lead and antimony, and a variety of others, for high voltage techniques requiring from 150 to 400 kilovolts. A 1/4-inch lead filter is used at present with the General Electric one-million volt x-ray generator.

In addition to a filter, occasionally a metal cone or a lead-glass cone is employed to restrict the primary radiation to the desired area of exposure. A cone is essentially made of a material offering considerable opacity to x-rays, and eliminates the radiation from the surrounding structures of the exposure field. The material may be iron, steel, or either one lined with sheet lead having corrugations so that any possible deflection of the rays from the cone are trapped in the grooves. Some manufacturers are using lead glass in their cone construction because of its low cost of manufacture and of its general appearance. These cones have various port dimensions so that various selections may be made for the restriction of the field of exposure. The scheme has met with considerable success.

It has already been noted that secondary radiations reaching the film are a constant menace to the production of a sharp, well-defined, and interpretable image in a radiograph. Several methods

were also suggested to minimize the effect of the fogging due to this dissemination of stray x-rays. Of these the Bucky diaphragm appears to lend itself to maximum efficiency in precluding the secondary radiations from the area of exposure. In use, it is interposed between the object to be radiographed and the film.

A Bucky diaphragm comprises a moving grid consisting of a series of lead strips interposed at definite intervals between strips of x-ray transparent material such as wood, bakelite, pure fibre, lucite, or other organic material. The lead strips are placed alternately with the radio-transparent strips, preferably of wood, and the plane of the arrangement forms a curvature whose radius is defined by the primary rays from the x-ray tube target. This radius, then, amounts to the focus-film distance, which is usually 25 to 36 inches depending on the type of diaphragm and its use. Generally this radius of curvature is specific with each diaphragm manufactured. It is, therefore, essential that the target-to-film distance conform to the radius of this curvature when employing a Bucky diaphragm in the exposure.

For exposures of short durations, from 1 to 30 seconds, the grid (the plate consisting of alternate strips of lead and wood) moves approximately 3 to 5 inches sideways, admitting through largely those radiations that are incident perpendicularly to its curvature. Long exposures, ranging from 30 seconds to 20 minutes or higher, however, require constant back and forth movement of the grid. With the target-film distance properly selected and the tube properly aligned, the movement of the grid, then, prevents the formation of a shadow of the lead strips in the radiograph. The oscillation of the grid, though prevents its shadow from becoming recorded in the film, offers an effective means of absorbing all x-radiations directed to the film from sources other than the x-ray tube target.

Aside from constant movement of the grid, the diaphragm should be so aligned that the principal ray from the anode surface falls at least approximately to the center of the exposure field. Failure to observe this simple procedure results in the appearance of grid markings in the radiograph. For instance, if the entire exposure field of the radiograph suffers from grid markings, the cause is attributable to the irregularity of the grid movement; if the markings are present in the center or are included about the

border area of the image, the condition indicates an incorrect distancing of the x-ray tube from the film; and, the improper alignment of the x-ray tube with respect to the Bucky diaphragm entails the appearance of grid lines on one side of the exposure field.

While the diaphragm is designed as an effective means for reducing the secondary radiation effect, a considerable amount of the primary radiation is absorbed by the apparatus, thus necessitating a longer exposure in the technique. This absorption is equivalent to a radiation energy of 50 to 70 per cent, and hence, in using a Bucky diaphragm the time of exposure should be increased 3 to 4 times that required without the use of the diaphragm.

7. Penetrameters and Their Use.—In order to determine whether or not a radiograph has the proper radiographic quality in that all unit detail structures are visibly delineated due to a proper exposure technique, it becomes desirable to place a specially-designed piece of the base metal, known as a *penetrameter*, on the object to be radiographed.

The penetrameters are standardized by various authoritative groups, and at present there are two types of penetrameters. One type consists of a ladder or a staircase arrangement made up of thin sheets of the base material of thicknesses ranging from 0.005 to 0.1 inch. Each step has an area of 1/2 inch by 1/2 inch with a 3/16-inch hole drilled in its center. In the radiograph, the step having the most detectable feature is compared with the corresponding thickness of the specimen. If the images of the two metals, the step and the corresponding section of the specimen, present optimum interpretable qualities and correspondingly identical densities, the exposure technique is considered to be accurate. On the other hand, if the density and the detail delineation of the two images are not compatible, improvement in the radiographic technique is indicated.

A more recently adopted penetrameter consists of a thin sheet of the same base metal and of the same density as the specimen to be radiographed. Each penetrameter has an area of 1/2 inch by 1-1/2 inches, and is of a thickness equal to 2% of the thickness of the section to be radiographed. For a magnesium alloy, this thickness is 3% of the thickness of the section under examination.

In each penetrameter, there are three holes having diameters respectively 2, 3, and 4 times the thickness of the penetrameter, as shown in Fig. 79. On one side of the penetrameter is attached an identification number made of lead alloy and which has a value equal to 50 times the thickness of the penetrameter. That is, if the thickness of a penetrameter is, for instance, 0.05 inch, the identification number will be $0.05 \times 50 = 2.5$, which indicates that this penetrameter should be used with a 2.5-inch section of

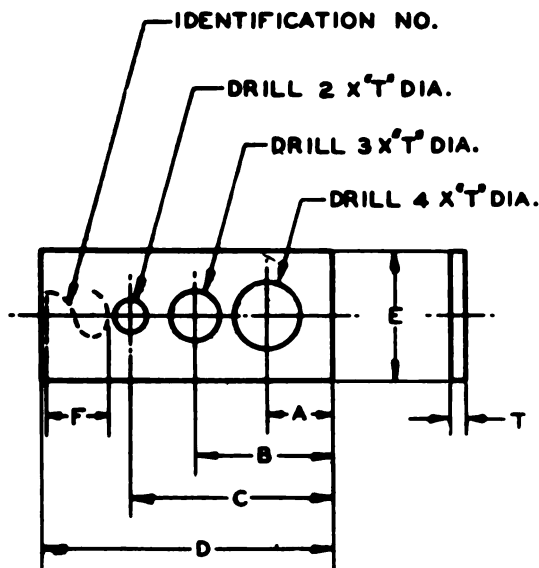


Fig. 79. Schematic Diagram of a Penetrameter.

the specimen to be radiographed. The diameter of the hole nearest the identification number will then be $0.05 \times 2 = 0.10$ inch, the second hole $0.05 \times 3 = 0.15$ inch, and the diameter of the third hole will be $0.05 \times 4 = 0.20$ inch.

For all metals having sections less than $1/4$ inch in thickness a penetrameter 0.005 inch thick is employed, and for magnesium and its alloys having sections less than 0.17 inch in thickness a penetrameter of 0.005 inch thickness is required.

A penetrameter is placed on each part to be radiographed for the duration of the exposure. It is usually placed on the section

of the base material which is furthest from the source of radiation and facing the tube target.

Table IX, below, gives the official specifications for the various dimensions of the penetrameter to be used with the various corresponding section thicknesses.

TABLE IX:—PENETRAMEETER DIMENSIONS CORRESPONDING TO SECTION THICKNESSES OF THE BASE METAL

Sections Up to and Including 2.5 Inches Thick.		Sections Over 2.5 Inches Thick.
A	1/4	1/2
B	11/16	1-1/16
C	1-1/16	1-9/16
D	1-1/2	2-1/4
E	1/2	1
F	1/4 Approx.	3/8 Approx.
T	Thickness of Base Metal 2%.	

The thickness of the penetrameter and the various holes in it form a criterion as to the density of the radiograph and to the minimum detail detectable. For instance, if the outline of the penetrameter is shown clearly in the radiograph, a definition of at least 2 per cent is indicated (which is equivalent to a sensitivity* of 2 per cent). If the first hole, which has a diameter of twice the thickness of the penetrameter, is clearly visible in the radiograph, the detail definition is said to be optimum, since structures as small as 4 per cent of the thickness of the specimen can be detected in a horizontal plane. The sensitivity of the radiographic process is also 4 per cent. If the first hole cannot be seen but the second is barely detectable, the definition featured by the radiograph is said to be good, since structures of the order of 6 per cent of the specimen thickness are visible (sensitivity 6%), and so on. If none of the holes are visible in the radiograph, the detail is then entirely missing, and a new exposure technique should be established. By this method, indeed, a sensitivity as small as 1/2% in either the horizontal or vertical planes may be

* Radiographic sensitivity is the ratio of the linear dimension of the defect to that of the base material expressed in percentage.

attained. It should be noted, however, that absolute reliance on penetrameters used on complex structures consisting of metals of varying densities should be restricted to special technique procedures.

If the outline of the penetrameter is clearly shown in the radiograph but none of the holes is detectable, the condition indicates one of incorrect alignment of the penetrameter in relation to the primary beam. The penetrameter should be so placed that its surface is at right angles to the radiation beam emanating from the target. At such a position of the penetrameter the rays are directed perpendicularly to the surface of the penetrameter, and, hence, pass through the holes without obstruction and produce a darker area which can be differentiated from the contiguous areas.

8. Photographic Factors of a Radiograph.—A radiograph is a shadow representation on a photographic film of the different densities or thicknesses of an object traversed by x-rays. It is constituted by the point by point recordings of the various x-ray intensities affecting the emulsion of the film. The variations of the x-ray intensities of the emergent beam striking the film are dependent upon the differences in densities, thicknesses, and composition of the object traversed. In a radiograph, more radio-opaque parts are represented by lighter regions, whereas more radio-transparent parts by darker regions. In fluoroscopy, the converse is true; more transparent parts are represented by lighter regions, and more opaque parts by darker regions or areas.

The degree of blackening of a radiographic film is generally referred to as the *radiographic density*. The density of the radiograph increases with increasing x-ray intensities, and the sharpness becomes accentuated with increased focus-object distance. Since the further the object from the source of x-rays the smaller shadow it casts upon the screen in its immediate vicinity, the distortion in the resultant image diminishes in an important degree. Just as the shape of the shadow of an object differs materially from that of the object itself when the latter intercepts the rays at an angle other than that normal to its plane, the radiograph may suffer from excessive distortion due to improper alignment of the object in relation to the focal

spot and the film. Close approximation of the object to the film will markedly aid in producing the desired purpose.

Visualization of the radiograph may be aided by directing the eye normally (perpendicularly) to the center of the image placed the same distance apart from the eye as the focus-film distance used for the exposure technique. If this is not found to be very convenient to the diagnostician, the eye-film distance should be at least 8 to 12 inches. If orientation of the radiograph is desired, it may be secured by indicating the right and left sides of the radiograph by means of suitable lead markers placed on one corner of the exposure holder during the exposure.

(a) *Radiographic Density*.—When the radiographic film receives the proper amount of x-ray energy so that the resulting image consists of properly balanced shades of light and dark shadows, insuring a ready distinguishability of the various thickness gradations together with minute detail structures, the radiograph is said to have the proper density.

The density of a radiograph is defined as the logarithm of the reciprocal of its transparency ($D = \text{Log } 1/T$) and represents the degree of blackening of the film upon exposure to a radiation. It depends upon the magnitude of the milliampereseconds used during the exposure and on the quality of the x-ray wavelengths. The higher the value of the milliampereseconds the greater the radiographic energy absorbed by the emulsion of the film, and hence a radiograph of increased density will result. Further dependence of the radiographic density on the target-to-film distance and on the applied potential may be shown by equation (84), in which the density varies directly with the kilovoltage but inversely as the square of the distance between the focus and the film. The focal spot size, however, does not affect the density of the radiograph.

The amount of blackening of a radiographic film is given by equation (83) as

$$D = \text{Log}_{10} \frac{I_0}{I}$$

in which, D is the radiographic density in some arbitrary unit (to be explained in the accompanying sections), I_0 is the inten-

sity of the incident radiation, and I is the intensity of the transmitted radiation.

To further elucidate the equation (83), let us assume that a certain radiographic film has such a degree of density that when an illumination of unit intensity is incident upon it the transmitted light will have an intensity only 1/10th. The ratio of the two intensities, then is 10 to 1. Thus, using the equation (83), we have

$$D = \text{Log}_{10} \frac{I_0}{I} = \text{Log}_{10} \frac{1}{.1} = \text{Log} 10 = 1$$

in which, I_0 is the incident radiation intensity, I is the intensity of the transmitted radiation, and D is the density of the radiographic film.

It will be noted then that the radiographic density of the film under consideration is equal to 1. If now another section of the film is tested and found that with the same value of the incident light intensity as given above the intensity of the emergent or transmitted light is 1/100th. Therefore, the density at this region will be given as $\text{Log } 100/1 = \text{Log } 100 = 2$. The discussion may be extended to any values of the incident and transmitted intensities for the corresponding densities.

(b) *Radiographic Contrast.*—The difference in radiographic density between two given areas of a processed film constitutes the contrast of the radiographic image. Assuming that the density of one area in a given radiograph is D_1 and the density of another area which is more dense is D_2 , the contrast between the two areas will be $D_2 - D_1$, the difference of the two radiographic densities. Let us further assume that the intensity of the incident radiation is I_0 and that of the transmitted radiation at area number 1 is I_1 , and that at area number 2 is I_2 .

From equation (83), the density at area 1 is equal to $\text{Log } I_0/I_1$, and that at area 2 is $\text{Log } I_0/I_2$. The contrast between the two areas will then be given as

$$D_2 - D_1 = \text{Log } I_0/I_2 - \text{Log } I_0/I_1$$

$$\text{or,} \quad D_2 - D_1 = \text{Log } \frac{I_1}{I_2} \quad (91)$$

From an analysis of the radiographic aspect of an image it may be inferred that the accurate interpretation of the radiograph depends on the ability of the observer to distinguish the contrast between contiguous areas having brightnesses of slight variations. The degree of the difference of contrast which is just perceptible is dependent upon the conditions under which a given radiograph is viewed and upon whether or not the transition between the areas under consideration is sharply defined. If one area gradually diffuses into the other without perceptible boundary then contrast is less readily observed, and hence the analysis of the radiograph is less successful.

The range of brightness for maximum perception varies between the limits of 0.10 to 100 candles per square decimeter. Under most favorable conditions, the difference of density which is perceptible is of the order of 0.01. Generally, with a brightness from a 500-watt incandescent lamp in a radiographic illuminator furnished with a diaphragm to vary the extent of the illumination to the film, a density as high as 3.2 may produce a sufficient contrast perception when bright areas are masked to restrict the field of visualization to the area of interest.

In determining the contrast quality of a radiographic film it is desirable to know how small a difference of exposure may be distinguished in the radiographic image. A film is said to have a high contrast if small differences in exposure time produce large differences in density. The contrast is further dependent on the conditions under which the processing of the film is conducted. In order that such differences in density may be solely attributed to the exposure technique, a standardized time-temperature processing (especially developing) should be strictly observed.

Other factors remaining constant, the higher the milliamperage of the x-ray tube the greater the radiographic contrast. Within a distance limit, and all other factors being equal, a higher kilovoltage (than that for normal technique) produces less contrast, but the visibility of the detail structure will be improved. If the magnitude of the applied kilovoltage that produces a satisfactory penetration is exceeded that which ensures a proper radiographic contrast the radiograph suffers from grayish (flat) appearance. On the other hand, too low a kilovoltage will cause

an excessive contrast with loss of detail. In order to obtain a proper contrast without particular regard to accentuation of the detail, the kilovoltage should be kept at a value just sufficient to produce the necessary penetration.

Increasing the time of exposure increases contrast, and decreasing it reduces the contrast of the radiograph. With properly

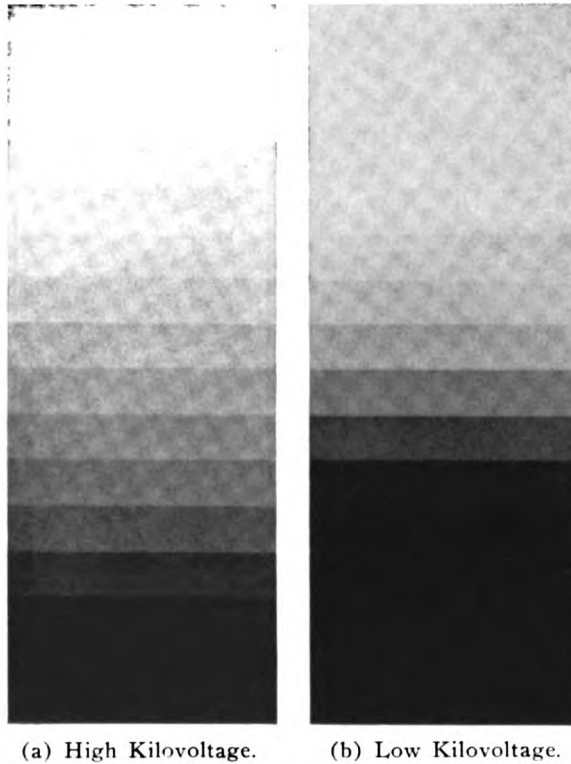


Fig. 92. The Effect of Kilovoltage In Producing Thickness Gradations.

chosen radiographic energy factors, the tendency of a small size focal spot toward producing a higher radiographic contrast and finer detail with whites and blacks appreciably better balanced is increased. The Bucky diaphragm in conjunction with a cone of approximate size proves an additional aid in obtaining the desired effect of radiographic contrast. Longer development of the film than that given as normal will likewise increase this quality.

It should be further noted that an increase in over-all contrast will result in loss of visibility of the radiographic detail. Therefore, when a high kilovoltage technique is employed, a low contrast together with visibility of small differentiation in the gradations of the different thicknesses are achieved. If, however, the part to be radiographed transmits x-ray intensities comparatively to a small extent, a technique offering a high contrast will be more preferable. The effect is further illustrated in Fig. 92, which presents two radiographs of an aluminum ladder consisting of various uniform thicknesses.

The radiograph in (a) is taken with a high kilovoltage technique, whereas a low kilovoltage technique is used in the radiograph shown in (b). These illustrations should assist in enabling one to determine whether a given specimen should be radiographed with a high or low kilovoltage technique. As a rule, structures of low atomic number require higher contrast, whereas those of high atomic number may be radiographed with higher kilovoltages for moderate contrast.

(c) *Definition of a Radiograph.*—The sharpness with which the visibility of a radiograph is defined is characteristic of the definition, or, detail, of the radiograph. The radiographic detail is constituted by the projected image of minute structural elements of the specimen examined. It was stated, above, that contrast is the difference of density of blackening of the contiguous areas in a radiograph. In order that a defective area becomes visible, the change in blackening of the boundary line (against the background) should be sudden and sharp, because such a change is more perceptible to the eye. A sharply defined image, then, has a high definition of detail.

The chief determinant in a radiograph for diagnostic purpose is the *definition* with which the radiographic detail is recorded. When desirable, a high quality of sharpness may be obtained by employing a fine-grain film without intensifying screens. A fine-grain film has relatively low sensitivity, and, therefore, is slow. If the part to be radiographed is thick and hence long exposure time is necessitated, metal foil screen may be used in the exposure holder to serve as intensifying screens. The time of exposure may then be shortened from three to eight times

depending on the character of the screen material used and on the applied voltage to the x-ray tube.

Fine definition is often prerequisite to accurate radiographic interpretation. Since proper definition is largely dependent on the visibility of the minutest detail structure, a high contrast does not necessarily mean to result in optimum definition of detail in the radiograph. Furthermore, since the radiographic density is a logarithmic function of the exposure energy, and is dependent on the development time and temperature, and on the character of the film (that is, its latitude, speed, grain size,

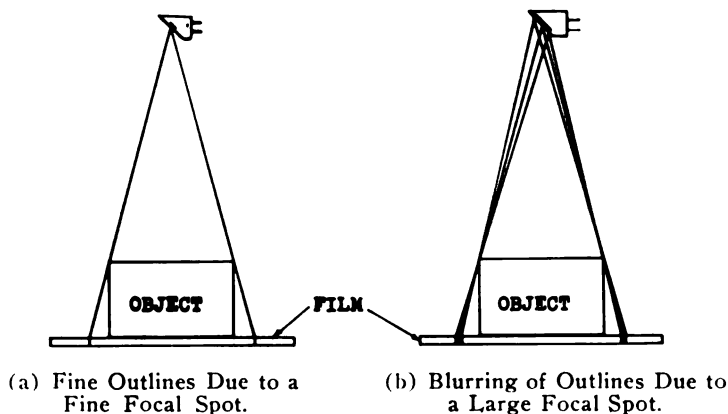


Fig. 93. Relation of Focal Spot Size to Definition of the Radiograph.

and selectivity, all of which remain constant for a given film), the exposure factors governing the optimum radiographic effect should be chosen within close limits.

The definition of a radiograph is further dependent upon the size of the focal spot. That is, the smaller the focal spot area consistent with the applied power required by the given technique, the more uniformly concentrated are the diverging rays. Consequently, a sharper and better-defined radiographic image will be achieved.

The relation between the definition of a radiograph and the size of the focus area is better understood by a reference to Fig. 93, which illustrates the formation of two images by the radiation from two different x-ray tubes having different focal spot areas. One tube, in (a), has a relatively very small focus

area, while that in (b) has a large focus area. The first illustrates the formation of a sharp image due to the projection of the radiation from a small source, whereas the second (in which the radiation propagates from many small sources) reveals a multiplicity of images of the object intercepting the radiation beam. The image in the latter case will be blurred or unsharp, and, therefore, the target-film distance should be increased to give the effect of a reduced focal area, thus improving the radiographic quality. Since a large focal spot permits the impression of a larger load on the x-ray tube than the fine focus, it is not necessary to increase the time of exposure if electrical factors are varied to compensate for a change in distance between the target and the film.

The energy applied to a rotating-anode x-ray tube having a fine focus may be increased as much as ten times that employed on a stationary anode of equal focal spot area. Since at maximum distances the definition of the image is improved, a fine-focus rotating-anode tube will still further curtail a reduction in unsharpness above that produced by an increase of target-to-film distance with consequent increase in applied load.

It will be obvious then that in order to secure the *optimum quality of definition* in a radiograph, the x-rays should proceed from as *small a focal spot* as possibly consistent with the loading capacity of the x-ray tube. A practicably *large target-film distance*, *short part-film distance*, and *proper alignment* of the object and the film in relation to the source of radiation become of special significance. Since the exposure time is proportional to the square of the distance, an x-ray tube having a focus twice the surface dimension of another may be used at twice the target-film distance to produce an identical quality of definition in the radiograph. But, owing to the radiation intensity varying inversely as the square of the distance, the time of exposure should be increased four times, unless an increase in the milliamperage or in the kilovoltage of the technique has been made.

(d) *Radiographic Distortion and Magnification.*—In every radiograph a slight magnification in the image of the specimen radiographed is prevalent. The effect is attributable to the diverging character of the x-ray beam leaving the focal spot.

If the radiographic image is magnified yet it retains the true shape and outlines of the part radiographed, the effect is pure magnification, and sometimes is referred to as *true distortion*. Such a magnification is uniform and its magnitude can be minimized by increasing the distance between the focal spot and the film and by decreasing the part-film distance (if such be possible).

If the magnification is not uniform, causing the image to appear distorted, or twisted, by losing the true shape of the part under consideration, the resulting image quality is said to have *false distortion*. False distortion may be reduced to a minimum by correct alignment of the tube target relative to the center of the exposure field of the material and the recording surface. The principal ray, which projects at right angles to the axial plane of the x-ray tube and is of the least divergent character, should be directed perpendicularly to the center (as much as is possibly convenient) of the area of exposure. If close approximation of the specimen to the film cannot be effectively achieved (due to the interposition of a Bucky diaphragm or due to the great thickness of the object) the ratio of the focus-film distance to the part-film distance may be increased to offset the tendency of the structures remotest from the film from becoming superfluously enlarged.

The phenomenon is illustrated in Fig. 63, in which the diagram in (a) represents an object placed between the target of an x-ray tube and the film. Since the principal ray is directed perpendicularly to the center of the exposure field and the film, the resultant radiograph possesses a true magnification of the object radiographed. It is true, however, that there will be present a slight false distortion of the structures near the edges of the part which are not in a perpendicular aspect with the central x-ray beam. Such a distortion is expected in every radiograph, and the effect may appear as elongated or foreshortened image depending on the angulation of that particular part in respect with the principal ray. In (b) the image is distorted, because the principal ray is out of the center of the field of exposure, and, therefore, the magnification is not uniform or symmetrical. The image of the object which is a square will become oblong in shape.

(c) *Latitude of a Film*.—The latitude characteristic of a

given radiographic film is the exposure range over which various detail delineations are satisfactorily revealed so as to be of diagnostic value. As stated in a previous occasion, the latitude of a film is directly related to the radiographic contrast. A film of high contrast possesses a low degree of latitude, and one having a low contrast will possess a wide latitude. A film of low contrast, and hence of large latitude, will record the various scales of blackening produced by a specimen of widely different thicknesses, while with a film of high contrast (small latitude) thinner sections of a specimen composed of several widely different thicknesses will appear extremely black and the thicker sections will appear very light so that small density changes due to a fine defect may be entirely lost in the radiograph.

It has been already observed that the kilovoltage is an inverse function of contrast. That is, the higher the applied voltage which produces the x-radiation a corresponding reduction in contrast will be curtailed. With a low kilovoltage technique the change in radiation intensity traversing different thicknesses will be greater, as the radiation of this quality will be more readily absorbed. Consequently, if a wide degree of latitude is desired in the radiograph, a slightly higher kilovoltage than that used in prevalent techniques will serve the purpose when other factors are adequately controlled.

It becomes evident then that if the part to be radiographed has a wide spread of total thicknesses, a film of high contrast should not be used because of the existing tendency to lose visibility of structural detail present in the higher and lower radiographic density levels. In the lower density levels contrast is lost because of loss of distinguishing differences between the light areas. Contrast is lost in the higher density levels because to view the darker areas legibly for diagnostic purpose is almost impossible with ordinary illumination employed in the diagnosis of radiographs.

Therefore, in selecting a film for radiographic work, the practitioner must decide whether he wants high latitude or high contrast in the film he chooses for any particular radiographic use. Usually a film of high latitude is preferable especially for a technique requiring short exposure time, as a slight error in estimating the exposure time can be compensated to a large

extent to obviate the subversive characteristics due to over-exposure that would be indicated in a film of high contrast. Again, choosing a film of high quality enters into the rendition of most desirable radiographic qualities.

CHAPTER VII

PHOTOGRAPHIC EFFECTS OF X-RAYS

One of the greatest strides made in the art of photography is the discovery that the halogen compounds of silver, such as silver chloride, silver bromide, and silver iodide, are sensitive to visible light. A photographic paper or plate is made by coating a plate of glass or a special type sheet of paper in the dark with one of these compounds and obtaining the image by the action of light. The first photographic silver salt utilized was silver chloride which required long exposure time to darken. Thus, it was impractical for use in a photographic camera. The latter salt, however, found great use until recently in photographic printing-out papers, in which process the sensitized paper is placed next to the negative plate or film and is exposed to the illumination from a high intensity incandescent lamp or sunshine.

A further advance in the art occurred with the use of silver bromide. In this case, instead of depending entirely on the action of light to form the image by darkening the sensitive paper subsequent to a long exposure, the paper is exposed to light for a short time and the formation of the image is continued and completed by the action of a chemical solution known as the "*developer*."

The year 1871 marks the utilization of gelatine-silver bromide for photographic plates for the first time. The scheme subsequently has been extended and modified in an endeavor to obtain increased sensitivity to specific spectral ranges and at the same time to render a finer grain structure to the emulsion responsible for the photographic quality of the plate or the film.

The familiar darkening of the film upon exposure to light has achieved supreme practical importance in radiography, which employs light rays of extremely short wavelengths already referred to as "x-rays." Since the photographic properties of x-rays are of a distinct character the sensitive emulsion of the film must be made radically different from that used in ordinary photographic films. The x-ray film must be not only sensitive to direct radiation of x-rays but also to the apple-green fluorescence of the

intensifying screens. There is not any known film emulsion, however, which will be affected by x-rays but not be sensitive to visible light. All emulsions of photographic films are specifically sensitive to one form or another of electromagnetic radiation. A further distinction due to x-ray film is that it must be capable of recording slight variations in density, thickness, or structural constitution of the various materials radiographed by providing adequate contrast and sharp detail delineation in the developed image.

Because of the rapid expansion of the facilities of various industrial plants and of the consequent increased demand for x-ray testing especially of structures bearing gravity on the safety of human life, the chief aim of modern radiography is being directed to speed factor without sacrifice in quality of the radiograph. This fact has further created a need for sensitized films specifically designed for industrial applications. Several leading photographic manufacturers have been lately producing radiographic materials that are found to present the ultimate as far as the present-day knowledge of the chemical and physical nature of the photographic emulsion is concerned—speed, sensitivity, and exposure latitude, combined with uniformity of grain structure and freedom from defects are what make the discriminate radiographer to conduct his radiographic work with ease of mind and confidence.

A great deal is contributed by such manufacturers as the Eastman Kodak Company, Agfa Ansco, Du Pont, etc., indeed, to the progress and the improvement in the quality of the radiographic film of the present day. Exposures which some years ago took several hours are now made with exposure intervals ranging from 1/1,000,000 second to several minutes. For this latter condition in radiography, mention is in appropriate order that the modern high-power x-ray tube together with ultra-speed intensifying screens have, however, contributed to a large extent.

As stated above, photographic films differ widely from one another, each having been designed to serve a specific purpose. Industrial radiography at present demands several distinctive types of films specifically designed to handle various applications from light metals to heavy alloys and steel with voltage ranges from 5 kilovolts to one-million volts or over.

The differences of film quality may be classified under two very

general headings: *photographic characteristics*, and *physical characteristics*. The former property refers to the speed, sensitivity, contrast, and exposure latitude, whereas the latter refers to the type of base (cellulose acetate, cellulose nitrate, soda glass, lime glass, etc.), graininess, antihalation feature or anti-fogging effect as in radiography, etc.

Aside from two different types of special films now commonly employed in medical radiography, the Eastman Kodak Company now manufactures three additional distinctive types of x-ray films to meet many of the present day requirements of industrial radiography. This important contribution to the x-ray field in industry comprises (1) *Type A* x-ray film of fine grain (optimum definition), high contrast (optimum visibility), and of low speed. It is suitable for radiography of light metals such as aluminum, magnesium, and their alloys, which are radiographed with voltages from 30 to 150 kilovolts. The film may further be employed for radiography of heavy metals such as copper, steel, and their alloys, and where x-rays generated by tensions of the order of one-million volts or over are used. Though the success of obtaining the highest radiographic quality will depend largely on the skill of the radiographer and the character of the technique employed, if the film is used by direct exposure, and, where necessary, with lead-foil screens of proper thickness, for radiography by million-volt x-rays and by radiations from gamma-rays, very satisfactory results will be derived from its use, since at the latter range of wavelengths the speed advantage of the calcium tungstate intensifying screens is not only small but the inherent graininess of the resultant screen image is considerably large.

In a previous occasion it was observed that the higher the potential used to produce x-rays (higher penetration) the smaller the contrast. The million-volt x-rays and gamma-radiations will have similar action relative to low contrast, and further will produce a relatively more grainy image than that characteristic to less penetrating x-radiations. This difficulty is overcome, however, by the use of the *Type A* Eastman Industrial X-Ray Film which possesses high contrast and fine grain size. Since speed is of no consequence with x-ray generators energized by a million-volt or over, owing to their high capacity of radiation output, the use of the *Type A* film for this purpose is entirely adequate. Compared

with the Eastman No-Screen film, the contrast between the *Type A* film and the former is approximately the same, with the exception that the no-screen film is twice as fast as the *Type A* film with gamma-radiation.

Next industrial film of importance is characterized by (2) *Type F* Eastman film. As has been referred to in an earlier section, high contrast and fine grain cannot be practicably achieved in combination with high speed, which is secured by large grain film emulsion. The *Type F* film is primarily intended for the radiography of heavy metals such as thick steel parts, and provides a high speed and contrast in this work when employed with calcium tungstate intensifying screens. The use of the latter is essential in order that adequate exposure of steel of thicknesses greater than 1-1/2 inches at 220 kilovolts, and greater than 3 inches at 400 kilovolts can be secured within a reasonable time. The film may be used for direct x-ray or gamma-radiation exposures, and where speed is not of any reasonable concern lead-foil screens may be employed to eliminate scattered radiation particularly that which undercuts the object.

For work requiring the highest possible speed with direct exposure, a third type of film (3), Eastman *Type K*, can be advantageously used for the radiography of especially light alloys, aluminum and magnesium, and for steel of thicknesses up to 1-1/2 inches at 220 kilovolts, 3 inches at 400 kilovolts, and 8 inches at one-million volts. It is also recommended for direct gamma-ray exposure.

In the writer's laboratory, a series of test exposures on beryllium-copper alloy was made using Eastman No-Screen, *Type F*, and *Type K* films for comparison of speed and sharpness of detail. In each test exposure tin-antimony screens were used and an H & D of 1.8 was taken as normal radiographic effect. The kilovoltage, milliamperage, and the focus-film distance were kept constant, only the time of exposure being variable. The tests indicated that the Eastman No-Screen film is approximately 35% faster than *Type F* film, but the latter appeared to present slightly higher sharpness of definition. For *Type K*, only one-half of the exposure required by No-Screen film was sufficient to produce the identical film density. In other words, by employing tin-antimony screens, the exposure speed of *Type F* film was found to be

approximately 2/3rd that of No-Screen film but had the highest sharpness of detail, whereas the No-Screen film was only approximately one-half as fast as the *Type K* film.

To obtain the advantage of intensifying action from metal screens, the applied kilovoltage to the x-ray tube, and the thickness and the character of the material must be taken into consideration. For instance, in the radiography of aluminum up to five inches no appreciable intensification benefit will be derived from metal foil screens, unless the voltage is raised beyond 150 kilovolts and the thickness of the metal is 5 inches or over.

With steel of 1/4-inch thickness, lead intensifying screens at tensions between 120 to 150 kilovolts will present slight intensification and hence a slight curtailment in the exposure time. In the radiography of steel of 1-1/4 inch thick, the intensifying factor of lead-foil screen will be approximately 3, a curtailment in exposure time to one-third that required with direct exposure. Using gamma-radiation, the lead-screen intensifying factor is only 2. The use of lead-foil screens or screens of heavy metals and their alloys further offers the advantage of attenuating the effect of secondary radiations originating from the specimen radiographed and that from auxiliary parts of the x-ray apparatus. Using one-million-volt for radiography of steel of thickness ranging from 1-1/8 inches to 7 inches, a 1/4-inch lead filter between the film and the cassette is found to improve sharpness considerably by diminishing the effect of the scattered radiations which tend to undercut the object.

A comparison of relative speeds of the Eastman *Type A*, *Type F*, and *Type K* industrial x-ray films with direct exposures present respective speeds of 17 with high contrast, 30 with medium contrast, and 100 with moderately high contrast for radiography of aluminum, magnesium, and other light alloys. In the radiography of thin steel parts, brass, bronze, beryllium-copper alloy, etc., the relative speeds of these films respectively compare as 19 with high contrast, 25 with medium contrast, and 100 of moderately high contrast. With million-volt x-rays and with gamma-radiation, the respective speeds are given as 20 for *Type A* with high contrast, 50 for *Type F* with medium contrast, and 100 for *Type K* with medium contrast.

The various film characteristics for Eastman industrial x-ray

TABLE X:—A COMPARISON OF EASTMAN RADIOGRAPHIC FILM CHARACTERISTICS.

Eastman Film	Application				Development With Kodak X-Ray Developer	
	Light Alloys	Thin Steel, Brass	Million-Volt X-Rays	Gamma-Rays	Normal Time at 68°F	Prolonged for Maximum Contrast at 68°F
Type A Relative Speed	17	19	20	20	5 min.	8 min.
Type F Relative Speed	30	25*	50	50	5 min.	5 min.
Type K Relative Speed	100	100	100	100	5 min.	8 min.
No-Screen Relative Speed	75	75	35	35	5 min.	8 min.
Blue Brand Relative Speed	30	25*	50	50	5 min.	5 min.

*Exposures should be made in conjunction with calcium tungstate intensifying screens. All others are used either with direct exposure or in conjunction with lead-foil screens.

films are summarized in a comparative respect in Table X.

In step with the progress of industrial radiography, the Agfa Ansco Company now offers four types of industrial x-ray films. (1) The *Agfa Non-Screen* x-ray film, employed for great majority of routine production work, is especially designed for rapid exposures with lead-screens or direct radiation. It is also used for diffraction work, low voltage exposures of plastics, paintings, flowers, textiles, etc., with speed as the deciding factor.

When maximum speed is desired with fine definition as secondary factor, (2) the *Agfa Industrial X-Ray Film* used with calcium tungstate intensifying screens is recommended especially when the thickness or the density of the material to be radiographed is excessive and where the output of the x-ray apparatus is limited. The film may further be used with lead-foil screens with direct exposure for radiographing objects with wide varia-

TABLE XI:—CHARACTERISTICS OF AGFA INDUSTRIAL X-RAY FILMS.

Type	Screens	Exposure Ratio	Recommended Developing Time at 68°F.	Industrial Applications
Non-Screen Type.	Direct or Lead screen	1	6	General Routine Work. Welds. Object of Uniform Thickness. Diffraction. Radium.
Industrial Type.	Direct, Calcium Tungstate, Lead screen	2	5	General Routine Work. Castings. Objects of Wide Thickness range. Radium. 1-million volt Exposure.
Superay A	Direct or Lead screen	4	6	Material of Uniform Thickness. Radium. 1-million Volt Exposure. Diffraction.
Superay B	Direct or Lead screen	10	6	Materials of Uniform Thickness. 1-million Volt Exposure. Diffraction. Flowers, Paintings, Spot Welds of light alloys.

tions in thickness and density. It is also recommended for radium and million-volt exposures, using lead screens, and requiring 2 to 3 times the exposure time required by the *Agfa Non-Screen* film.

In recognition of modern requisites of high contrast and fine definition essential in the detection and diagnosis of minutest defects in a part radiographed, the Agfa Ansco recently has introduced two additional screenless-type films, designated as *Superay A*, and *Superay B*, to supplement the fast *Agfa Non-Screen* film.

The *Agfa Superay A* film (3), has higher contrast, finer grain, and requires 4 times more exposure than the *Agfa Non-Screen* type film. It may be used for radiographing aluminum and magnesium alloys with low kilovoltage exposures, and heavy metals with radium and million-volt exposures. Either direct or lead-screen exposure may be employed with this film.

A fourth type Agfa film is characterized by the *Superay B* film (4). It is designed to render highest contrast with finest definition owing to its fine-grain emulsion. Its speed is approximately one-half that of *Superay A* film. When used with the million-volt x-ray generator, various gradations of thicknesses of

the material are defined sharply and with optimum contrast. Of the four types of Agfa films, the *Superay B* type renders the highest detail visibility, high contrast, and long scale of gradation in both low and high voltage ranges of exposures.

Table XI illustrates the various applications and characteristics of the four types of Agfa industrial x-ray films.

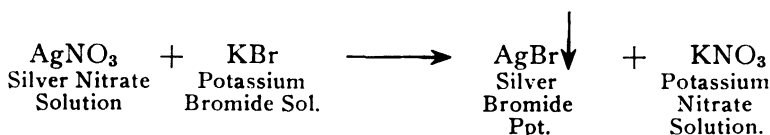
To further aid the radiographer, the various x-ray film manufacturers have also developed direct duplicating films, whereby contact films or reproductions of the original radiographs may be made without the necessity of an intermediate positive. This is accomplished by a contact exposure of the original radiograph on a specially prepared auto-positive film and developing the latter film either in an ordinary x-ray developer or in a specially compounded developing bath. Notable saving in time and in material is thus secured by making the reproduction of any radiograph in only one step. These films are obtainable through competitive manufacturers of photographic equipment and supplies.

1. The Radiographic Film.—Modern x-ray film consists of a transparent cellulose acetate base, 0.2 mm thick, coated on both sides with a layer of radio-sensitive emulsion of a thickness approximately 0.001 inch (25 microns). This emulsion consists of a colloidal suspension of silver bromide with a small addition of silver iodide in a solution of gelatin, which when dry forms the prevalent x-ray film.

The sensitive emulsion of the film is prepared by dissolving gelatin in warm water and adding the right quantity of either potassium bromide or sodium bromide and dissolving it in the gelatinous solution. An equivalent quantity of silver nitrate crystals to completely react with the bromide salt present in the gelatin solution is dissolved in distilled water in a separate container. The two solutions, then, are slowly mixed in a dark room which may be illuminated with a ruby safelight. The addition of silver nitrate, for instance, to potassium bromide solution produces a pale yellow insoluble precipitate of silver bromide which is sensitive to white light. This precipitate in the absence of gelatin would settle down to the bottom of the solution, but due to the emulsifying property of the gelatin the precipitate remains in suspension dispersed uniformly in the solution. The liquid in this state is known as the *emulsion*, which when uniformly coated

over the surface of a celluloid base and set aside to dry forms the radiographic film.

The chemical reaction between the potassium bromide and the silver nitrate that occurs when the two are mixed together may be given as follows:



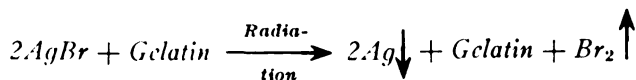
As silver nitrate precipitates, the solution is rendered a milky appearance, which is set aside to jel; and, after having been washed with distilled water to remove all soluble salts, the emulsion is remelted at a gentle heat, and applied uniformly on both sides of a sheet of cellulose acetate base by dipping it into the suspension or by means of rollers. When dry, each layer of the emulsion measures about 0.001 inch or 0.0025 centimeters in thickness.

The different degrees of sensitiveness of films may be obtained by the addition of a small amount of one of the various sensitizers such as uranine, eosin, erythrosin, quinoline red, etc., to the silver bromide emulsion. The photosensitization to various intermediate wavelengths between blue to infra-red may be achieved by the following sensitizers in their respective order: Chrysaniline, eosin, cyanine or methyl violet, nigrosine, dicyanine or neocyanin. The mode of action of these compounds in producing sensitization in the film emulsion is to influence the speed of blackening and the behavior or response of the silver salt to specific wavelengths desired.

A further dominating fact which has become recognized as exerting an influence on the sensitivity of the film emulsion is the size of its grains. This property is dependent upon the temperature and the duration of heating the colloidal silver emulsion before it is applied to the surface of the celluloid base. A more sensitive emulsion is one which is heated to a higher temperature and sustained at a longer period than an emulsion which is slow in its photographic action. The grain size is then a direct function of the temperature and the duration of the heating, the former being of the order of 212°F. or over. This process of

heating the emulsion at a sustained temperature is known as "*ripening*." Emulsions having grains of diameters between 0.2 micron to 0.4 micron are over 20,000 times less sensitive than films having grain diameters of between 2 to 4 microns. The former is known as fine grain film and is comparatively slower than the latter which is faster because of its relatively large grain size.

2. The Latent Image.—The exposure of the film emulsion to x-rays causes a photochemical change in the silver bromide in that an intrinsic image commonly known as the "*latent image*" is produced in the sensitized emulsion. This change, whose exact nature is unknown, may be attributed to the partial reduction of the silver bromide to metallic silver in the presence of gelatin and light. It is also possible that Br_2 is released from the decomposition product. Thus, the invisible impression is formed by the ultra-microscopic crystalline platelets of silver largely oriented in parallel aspect to the surface of the emulsion and forming the *nuclei* or *centres* around which other exposed aggregates of silver particles are centralized and become visible upon development of the film. The equation expressing this relation may be given as



The development (or, chemical reduction) of a grain of silver bromide is dependent on the size of the grain and on the quantity of radiation received by it. As we have stated above, larger grains are more amenable to the action of light or x-rays than smaller grains. When different emulsions are compared, grains of identical size and shape may differ in their sensitivities. In a film of good quality, the dispersion of the silver grains in the sensitized coating is very uniform. The nuclei begin to form as soon as light strikes the silver bromide crystals, and they increase in number with prolonged exposure. The development, however, starts from centres situated in the surface layers. The size of the grains in an x-ray film is much larger than that of photographic films in general use.

The quantity of silver liberated per unit emulsion area in the

process of exposure of the film to the radiation can be measured by the degree of blackening produced in the developed emulsion. The blackening is dependent upon the *intensity*, *quality* (wavelengths), and *duration of the radiation*, and upon the *character of the developer* and on the *extent of development* of the film. Measured optically, the degree of blackening D may be expressed by the relation given in equation (83).

It has been further shown that the blackening of the film (radiographic density) is a direct function of the exposure tension (applied potential to the tube) and that the exposure energy is inversely proportional to the sensitivity of the film and also to the third power of the exposure tension, as shown by the following expression:

$$E = K \frac{1}{V^3 s} \quad (92)$$

where, E is the exposure energy in watts, K is a constant characteristic to the exposure, V is the applied tube potential, and s is the sensitivity of the film.

Fig. 93 represents a schematic diagram of the cross-section of a double-emulsion radiographic film. A radiation quantum of

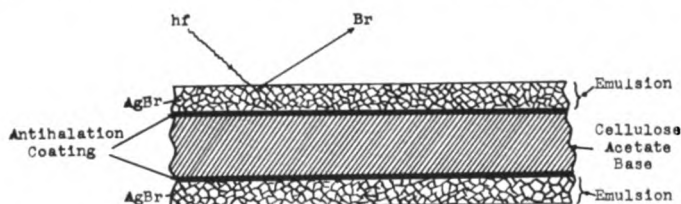


Fig. 93. Photochemical Effect of Radiation on Silver Bromide Crystals.

energy hf as it strikes a crystal of silver bromide, the latter is decomposed into atomic silver and bromine, which latter may or may not leave the emulsion until the film is developed. In the process, the silver bromide has undergone partial reduction, which reaction becomes more complete when the film is developed. The crystals which have not been affected by development are removed in the process of fixation in a hypo solution.

It should be further noted that the greater the number of radiation quanta striking the film emulsion and greater the energy

transferred to the silver bromide crystals a larger number of centres will be formed in the emulsion of the film. That is, the higher the intensity of the incident radiation and the greater the energy absorption by the film the resultant density of the film will be correspondingly greater.

3. The Chemistry of Processing.—We have already noted that when the sensitive emulsion of the film is exposed to the radiation from an x-ray tube, a latent image is formed by the reduction of some of the silver bromide crystals to black metallic silver. The exposure renders the silver salt to become highly amenable to the action of a reducing agent, called "*developer*," in which the image becomes further defined by the removal of the bromide ions from the exposed silver bromide salt, leaving in suspension in the gelatin black silver grains in exactly the same position as that of the silver bromide crystal from which it was formed. This process in which the bromide ion is removed from silver bromide by the action of the developer is known as *reduction*. (The term "chemical reduction" should not be confused with the term "reduction" as applied to negatives, in which latter process it refers to the removal of some of the silver grains from an over-dense negative.)

The silver bromide grains in the unexposed portions of the sensitive coating of the film remain unaffected by the action of the developer. The salt, then, can be removed upon additional treatment of the film in another solution known as the "*fixer*." The only economical chemical that will dissolve silver bromide and remove it from the emulsion is sodium thiosulphate, $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$, usually known to the photographic trade as hypo. Sodium thiosulphate forms a complex soluble silver-sodium-thiosulphate, having a formula $2\text{Na}_2\text{S}_2\text{O}_3 \cdot \text{Ag}_2\text{S}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$. In an acid solution of sodium thiosulphate, the image becomes permanently fixed.

After the film is exposed, its photographic processing consists of its treatment in the developer, rinsing in water for about 10 to 15 seconds, further treatment in the fixing bath, and finally of washing it from 20 to 25 minutes and drying. The resultant radiographic image consists of black metallic silver dispersed in the gelatin in various degrees of gradations to form the different detail structures of the object radiographed.

The following formulae, which have met with notable success in industrial radiography, disclose the ingredients of developers and replenishers to be used in tanks, and are ideal for use even in hot weather:

EASTMAN DEVELOPER

(Formula D-19b)

Water (about 125°F., or 52°C.)	3 gallons
Elon	1-3/4 ounces
Sodium Sulphite, Desiccated	3 pounds
Hydroquinone	7 ounces
Sodium Carbonate, Desiccated	2 pounds
Potassium Bromide	3 ounces
Cold water to make	6 gallons

Each chemical is dissolved individually in small volumes of hot water. A small amount of sodium sulphite is added to elon and to hydroquinone in solution to prevent oxidation of these reducing agents. The individual solutions are mixed in the following manner:

1. Mix elon and hydroquinone solutions together.
2. Mix sodium sulphite and sodium carbonate together.
3. Add the potassium bromide solution to the solution of sodas.
4. Add the first solution to the combined solution of sodas and bromide.
5. Add the remaining volume of cold water to make 6 gallons of cold developer.

When used at 68°F. (20°C.), proper radiographic contrast will be achieved within 5 minutes. Greater or lesser contrast may be obtained by developing the film respectively for longer or shorter time than specified.

An excellent x-ray developing bath emanating from Agfa Ansco research laboratories offers the following formula to be used with all x-ray films at 65°F. for 3-1/2 minutes for optimum results:

AGFA X-RAY DEVELOPER

Metol	19 grams
Hydroquinone	39 grams
Sodium Sulphite	260 grams
Sodium Metaborate	130 grams
Potassium Bromide	36 grams
Sodium Hydroxide	14 grams
Water to make	1 gallon

Dissolve the chemicals in the order given.

AGFA X-RAY DEVELOPER REPLENISHER

Metol	58 grams
Hydroquinone	78 grams
Sodium Sulphite	260 grams
Sodium Metaborate	520 grams
Sodium Hydroxide	56 grams
Water to make	1 gallon

Dissolve the chemicals in the order given.

In using the above developers, a 15-gallon tank of developing solution should be refilled after approximately 1100 to 1200 14" x 17" films have been developed. The useful life of the developer may be divided into three periods. When the developer is freshly put into the tank, and about 450 14" x 17" films have been developed, this period may be referred to as *Period A*. *Period B* comprises the next interval of developer life when about 400 additional 14" x 17" films are processed. In *Period C*, 200 to 250 14" x 17" films may be developed, subsequent to which the developer usually becomes completely exhausted.

Each time a radiographic film is removed from the developer, the emulsion, which has been completely soaked in the solution and may retain as much as 1-1/2 to 2 ounces of the developer, reduces the content of the tank by this amount. Therefore, in order to keep the developing solution at a constant level, fresh solution, known as *replenisher*, should be added from a stock supply. Throughout the useful life of a 15-gallon developer, the addition of the replenisher solution amounts to as high as 54 gallons, in which latter case as many as 4000 14" x 17" films may be processed before the developer is discarded.

As the developer gradually becomes weaker from one period to another, the development time should accordingly be prolonged. The exact time may be obtained by a reference to a development time indicator supplied by the manufacturer of the particular film and the developer.

After development, the emulsion of the film, which contains the image consisting of metallic silver, together with unexposed grains of silver bromide, is treated in the fixing bath to make the image permanent. This treatment removes all the unaffected silver bromide from the emulsion, leaving only the image-forming grains of metallic silver in suspension in the gelatin.

A fixing bath in its simplest form consists of a solution of approximately 35 per cent of sodium thiosulphate (also known as sodium hyposulphite), in which silver bromide is very soluble. It is desirable, however, that a fixing solution possess, aside from the property of dissolving silver bromide, the power of neutralizing the alkaline developer retained by the film, thus stopping further development. The fixing bath is further intended to harden the gelatin of the film which has become somewhat swollen and softened. A hardening agent such as potassium alum or chrome alum in combination respectively with acetic acid or sulphuric acid will produce this end.

An acid fixing bath which has rendered satisfactory results is given in the following formula to be used with x-ray films:

X-RAY FIXING BATH
(Formula F-10)

Solution A

Sodium Thiosulphate	16-1/2 pounds
Water (at 125°F., or 52°C.)	3 gallons

Solution B

Sodium Sulphite, Desiccated	6 ounces
Kodalk (E.K.Co.)	1-1/2 ounces
Acetic Acid	54 fluid ounces
Potassium Alum	18 ounces
Water (at 125°F., or 52°C.)	6 quarts
Dissolve the chemicals in the order given.	

Each chemical should be completely dissolved in the respective solution before adding the next. When the solutions are cooled to room temperature, the *Solution B* is added slowly to *Solution A* with constant stirring. Finally, sufficient cold water is added to the combined solutions to make the total volume 6 gallons.

In discussing the function of the different chemicals which participate in bringing about the desired image in the emulsion, reference should be directed first to the behavior of the various agents under conditions of specific character. For instance, in a developer containing elon (metol) alone the image appears very quickly but the radiographic density comes up slowly. In the case of a hydroquinone developer, the image occurs very

slowly but the density is acquired steadily and at a more rapid rate. It is evident then that elon has higher reduction power than the hydroquinone. Thus, the combination of hydroquinone and elon appears to be the logical solution in the preparation of a developer of which consistent results are to be expected.

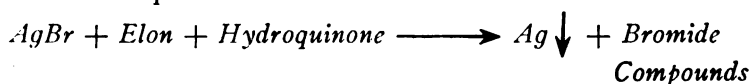


Fig. 94. Eastman Development Time Indicator For Eastman Industrial X-Ray Films.

Many of the developing agents require an alkaline medium for their proper action as reducing agents. For instance, hydroquinone when acting alone as a reducing agent requires caustic alkalis such as sodium hydroxide or potassium hydroxide, whereas Elon may be used in a mildly alkaline medium such as sodium carbonate. The quantity of the alkali in a developer must be strictly controlled, as when there is too much alkali present, the film tends to acquire a chemical fog, while too little alkali reduces the rate of action of the developer. Swelling, frilling, or blistering of the gelatin may occur by an improper quantity of the alkali in the solution.

Each ingredient of the developer entering into the production

of the necessary chemical change in the emulsion to form the image has a specific function, which may be explained as follows: Elon and hydroquinone, in an alkaline medium, act as reducing agents and convert the silver salt (silver chloride, silver bromide, or silver iodide) into metallic silver. This reaction may be illustrated in an equation form as



It is this reduced metallic silver that gives rise to a change in color of the original emulsion from a pale yellow to black or gray appearance, depending on the intensity of the radiation received by the film. As a result of this change, the latent image appears as permanent impression. Such a transition from a compound (silver bromide) to one of elementary metallic form is favored in a mildly alkaline medium, and hence the use of sodium carbonate or sodium metaborate in the solution. Moreover, since the gelatin must be softened before the penetration of the developer into the emulsion is rendered certain, the latter alkali makes this condition possible.

The developer is very susceptible to reaction with oxygen from the air if the lid of the tank is not replaced after the films are removed from it. This will further cause an undue loss of strength of the solution in course of time. Thus, a definite quantity of sodium sulphite is added to the developer to prevent this trouble. Sodium sulphite has a strong affinity for oxygen and thus combines with it to form sodium sulphate, preventing the developer from oxidation. In this respect, then, sodium sulphite is said to act as a preservative.

To restrain the reduction of the silver bromide crystals which have not been exposed, a small quantity of potassium bromide is added to the bath to yield bromide ions, which further slightly retard the action of the developer on the exposed silver salt. Consequently, the chemical reaction sustained by the developer will be less violent, thus producing clean-cut gradations of black and white in the image. This will further prevent a possible formation of chemical stain in the radiograph.

The film, after having been developed under controlled time and proper temperature, is rinsed in water for about 10 to 15

seconds and then immersed in the fixing bath. This bath permanently fixes the image in the emulsion by removing from it all unexposed silver salts. Since the fixer contains an acid, such as acetic or sulphuric acid, as soon as the film comes in contact with this solution further development is at once suppressed. The presence of potassium alum and boric acid in the solution produces hardening of the gelatin of the film emulsion. Boric acid further diminishes the sludging tendency of the basic aluminum sulphite from the bath.

Sodium thiosulphate is the chief fixing agent in a fixing solution. It dissolves, and removes from the emulsion, all the silver salts that are unaffected during the exposure of the film. Sodium sulphite extends the usefulness of the bath, which becomes useless when it has lost its acidity and that it requires a longer time for the image to clear than the usual time. An exhausted fixing bath indicates that the hypo present in the solution has combined almost completely with the silver to form complex silver-sodium thiosulphate.

While the above formulas are some aid to the x-ray practitioner, in many instances it is more convenient to use prepared x-ray developer and fixer solutions which are furnished by local photographic supply laboratories. Frequently, it may become desirable to prepare the processing solutions right in the x-ray laboratory. In that event, prepared developer powders and fixer powders supplied by the film concerns and recommended for use with their films will be found advantageous as the extra labor involved in measuring and mixing the ingredients from bulk chemicals is offset by the convenience and the saving of time thus realized. These chemicals, which are obtainable in packages sufficient to make from 1 gallon to 50 gallons may be procured from the Eastman Kodak Company, General Electric X-Ray Corporation, and other leading manufacturers of photographic supplies.

Depending on the amount of work done in an industrial x-ray laboratory, the processing solutions are made in quantities of 5 gallons to 100 gallons to be used in tanks large enough to accommodate at least from six 14" x 17" films up to eighty films respectively. During the treatment of the films in the developer, especially when they are first placed in the solution, it is

essential that they be agitated from time to time to insure uniform development by removing the air-bubbles that may be adhering to the surface of the films, particularly when a large number is inserted into the bath at the same time. Likewise, during immersion of the films into the fixer, the agitation should be repeated, which further hastens the arrest of development.

Unless processing is done in trays, the agitation of the films in the respective processing baths will be greatly simplified by using a film hanger. Figs. 95 and 96 clearly indicate the procedure of attaching the film to the hanger.



Fig. 95. Attach Bottom Clips to the Film First.

X-ray exposure techniques are usually standardized in routine radiographic work. But, such standardization cannot be relied upon unless at the same time reasonably accurate control has been exercised throughout the processing of the film. In order to achieve this end, the exposed film should be developed for a definite interval of time and at a specific temperature. The normal developing time for a radiographic film is 5 to 6 minutes at between 65°F. to 68°F., depending on the character of the chemicals used and on the potency of the bath. This also depends on the type and make of the film. The fixing of the film generally takes about 10 minutes to complete the processing. Under these conditions, a standardized time-temperature processing

becomes an assured measure in checking up on the correct radiographic factors employed for the exposure.

With latest industrial x-ray films, it appears that 68°F. is the most favorable temperature from the standpoint of both chemical reaction and of preserving the firmness of the gelatinous emulsion. To retain a constant developer temperature, an automatic controlling unit may be installed around the developer tank. Such a system offers an effective means of controlling the temperature at all weather conditions.

The above time-temperature values apply only to a developer

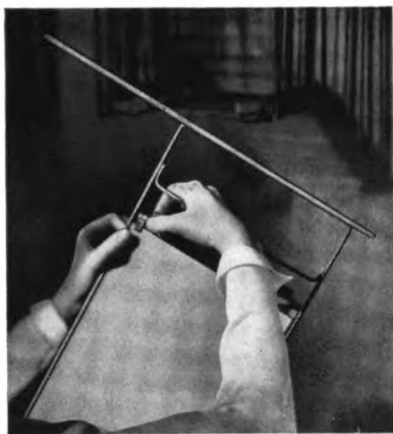


Fig. 96. Next, Attach Two Top Spring Clips.

of comparatively normal strength. As the developer becomes weaker by use, it takes a longer time for the image to appear. The rate of development is further affected by the temperature of the solution. The rate of development increases at temperatures above normal (68°F.) and decreases at temperatures below normal. These changes may be compensated for by varying the development time. Charts particularly prepared for this purpose may be consulted for proper development time. A relative time-temperature indicator is shown in Fig. 94. It is prepared by the Eastman Kodak Company for use with films and processing solutions of that concern.

The time-temperature indicator has a dial with arrows at-

tached to its face and die-cut windows. When the arrow at the bottom is turned to the figure corresponding to the temperature of the solution, there appears through the window and indicated by the smaller arrows the correct interval times with the developer at any of its three stages of exhaustion. Every processing technician should be provided with information of this type for the particular type of developer in use in his department. A copy of such an indicator or an equivalent chart may be procured from



Fig. 97. A Convenient Thermometer Which May Be Attached to the Rim of the Processing Solution Tank.

the photographic supply firm which furnishes the processing solutions or the prepared chemical powders.

A convenient method, which can be easily remembered, to determine the correct development time interval is to expose one-half of a 5" x 7" film, to develop it in a fresh bath at 68°F., and then to take accurately the time for the image to appear. By multiplying this quantity by 10 the correct development time interval is obtained.

The factor 10 is procured on the assumption that using a fresh developing bath at 68°F. the image appears within 30 seconds, and development is complete in 300 seconds or 5 minutes. Three hundred is then divided by 30 which gives the factor 10.

To illustrate, a 5" x 7" x-ray film, loaded in an exposure holder, may be covered partially with a 1/4-inch sheet of lead and ex-

posed to x-rays at 75 *Kv.P.* and 10 *M.A.* for 2 seconds at a target-film distance of 36 inches. The film, then, is removed under a safety lamp in the processing room and cut into one-centimeter strips. A 500-Cc beaker is filled with the fresh developer, and these strips are dipped into it one at a time, recording the time in which the image first appears. Assuming that this time is 25 seconds, the correct development interval may be determined by multiplying 25 by 10 which gives 250 seconds, or, 4 minutes and 10 seconds.

All processing conditions remaining satisfactory, a simple rule in determining the cause of an abnormal density or contrast in a radiograph may be summed up as follows: If the radiograph is unnecessarily dense and the image is partially obliterated from excessive blurring an over-exposure is indicated, and reducing the milliamperage or the exposure time for the next exposure will usually improve this condition. If the radiograph lacks the proper detail and contrast, and the parts are almost indistinguishable, an under-exposure is indicated, and the condition usually can be remedied, when making the next radiograph, by increasing either the milliamperage or the exposure time. In case the image is either gray or over-contrasty, the condition indicates respectively an over-penetration or under-penetration. For the first case, a decrease in the kilovoltage is recommended, while for the second an increase in the kilovoltage is required, for the next exposure.

In view of the fact that the exposure factors used on a given machine cannot always be applied to radiographic work on another machine, due to differences arising from rectification of the current furnished to the tube, to differences in installation parts or electrical devices materially affecting the nature of the electric power or its wave-form, etc., it will be found more advantageous if the radiographer standardizes a routine technique for various specimens feasible to conditions on his particular equipment. These findings may be recorded on appropriate chart forms for routine use.

4. Sensitometric Relations of a Radiograph.—The science of analysis by means of numerical quantities of the emulsion properties, such as speed, contrast, exposure latitude, density, development rate, exposure intermittency effect, and others is

known as *sensitometry*. In the quantitative sensitometric analysis of a given radiographic film, the procedure consists of making a series of x-ray exposures on the film (preferably with direct exposure), processing it under standardized time-temperature conditions, measuring the various densities of the various test exposures by means of a densitometer, and finally plotting a curve with the different densities obtained against the logarithm of the exposure energies employed for the exposures. The resulting curve, which is characteristic to the film under the given conditions, is studied and interpreted.

In a previous occasion it was stated that the density produced in a given area of a radiographic film depends on the quality and on the intensity of the radiation incident upon the film emulsion, and further on the conditions under which the processing of the film is carried out. This dependency further varies with different types of films and moreover with different makes. Therefore, in the sensitometric analysis, it will be more expedient to perform measurements on the same film and varying each of the controllable physical factors singly and under conditions similar to those in making a radiograph.

The test film under consideration is shielded with heavy sheets of lead so that only a small area (about 1 square inch or less) at a time may be exposed to the radiation from a constant intensity beam of x-rays. That is, the kilovoltage, milliamperage, and the target-film distance are kept constant throughout the procedure. Equal areas are subjected to the radiation, each receiving an exposure greater by a constant factor (for instance, each step is increased by an exposure of 2 seconds) than the preceding area. A series of ten or twelve exposures will be sufficient for plotting a characteristic curve as shown in Fig. 98. The film, then, is developed under carefully controlled time-temperature conditions, with known potency of the developer, fixed properly, and dried.

Subsequent to the processing and drying of the test film, a measurement of the density of each exposed area is made by means of a densitometer, shown in Figs. 99 and 101. The data thus obtained are the various densities of the test areas of varying exposure times. The numerical values of the density readings obtained from the instrument are plotted against the correspond-

ing logarithmic values of the exposures. The curve thus obtained represents the various emulsion properties which are characteristic to the film under test. Other curves similar to that shown in Fig. 98 may be obtained for each type of film and for each development time interval.

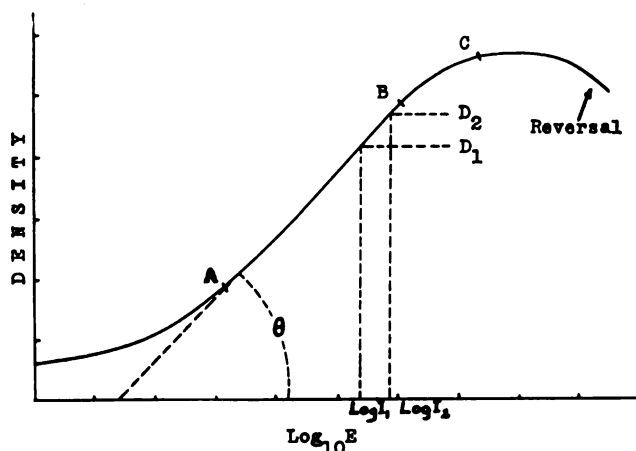


Fig. 98. Characteristic Curve Showing Densitometric Properties of a Film.

The densitometer shown in Fig. 99 is of the balanced electric circuit type so that in operation it is not affected by fluctuations of the line voltage or other electric disturbances, a condition requisite of every densitometer if accurate results are expected. The balancing circuit is of the Wheatstone bridge type. One side of the bridge has two fixed resistances whereas the other side is constituted by two sensitive photoelectric tubes, which, when illuminated by equal light intensities, will balance the circuit as indicated by the electron indicator connected in the bridge.

In operation, the device is connected to a 115-volt 60-cycle alternating current source, and the switch is turned on. This operation at once starts to warm up the various tube filaments in the circuit. The film of unknown density is placed over the field 1, shown in the figure, and a beam of light passing through the aperture 2 traverses the film and falls on a photoelectric cell located in the arm 3. The dial 6 is rotated until the electronic indicator 5 just closes, when, the circuit is said to be in

by M. H. Sweet, *Journal of the Society of Motion Pictures*, February, 1942, Pages 148-170. The instrument, shown in Fig.

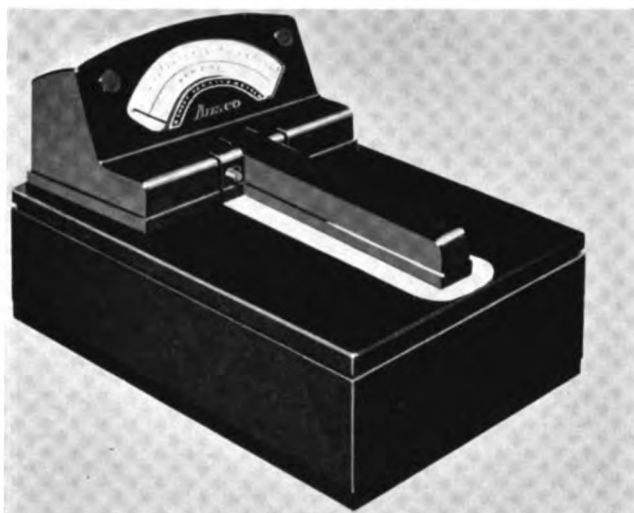


Fig. 101. The Sweet Direct-Reading Densitometer.

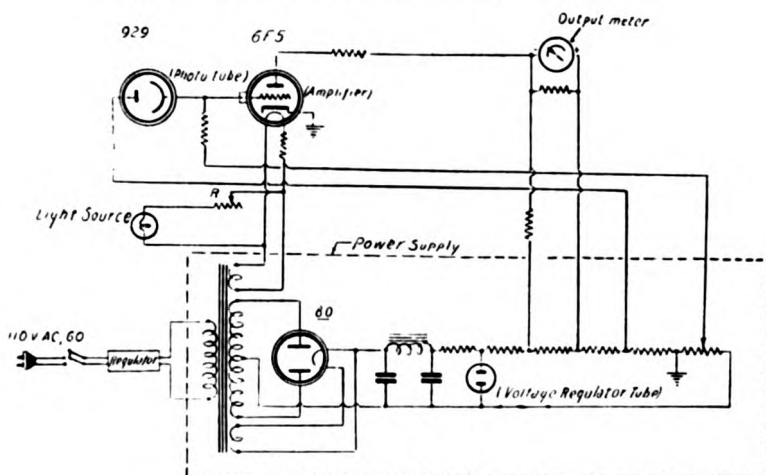


Fig. 102. Circuit Diagram of Sweet Densitometer.

101, has a single phototube connected directly to the grid of a 6F5 amplifier tube. The light incident on the photoelectric tube creates a small photoelectric current which is amplified and di-

rected into a micro-ammeter. This latter meter is calibrated to register density from 0 to 3.0 D.U., its deflection being directly proportional to the plate current, which in turn is proportional to the amount of light transmitted from the film of unknown density and incident on the phototube. The circuit diagram of the instrument is illustrated in Fig. 102.

Generally, the radiographic exposure technique for a given object having been well standardized, a densitometric measurement on different exposures of identical specimens will become an index to the effectiveness of the developer. Furthermore, prolonged usefulness may be obtained from a developer on which periodic densitometric checks are made. This property of the developer to produce contrast difference during its effective life may be quantitatively referred to as *gamma effect*, which is contrast divided by the logarithmic difference of exposure energies producing this contrast.

Referring to Fig. 98, the portion of the curve represented by OA is known as the *toe* of the curve. This region further represents an extreme under-exposure. For greater exposure values, the exposure differences are reproduced as density differences, and these are indicated by the straight-line portion AB of the curve and define the usable range in negative making. In this region, the density of the negative increases in direct proportion to the logarithm of the exposure energy. The region above B is characteristic of over-exposure. The curve gradually falls and becomes horizontal beyond C , with exposure differences no longer recorded by the corresponding density differences. Further increase in the exposure (or development!) will cause the curve to incline below the horizontal, when, reversal of the image is indicated.

The straight-line portion AB of the curve is the region of correct exposure, and the density difference between any two points on it is in direct logarithmic ratio to the corresponding exposure energy difference. For instance, assuming that the density of a given area in a radiograph is D_2 , indicated by the broken lines in Fig. 98, and the density of a contiguous area is D_1 , the contrast between the two areas will be the difference between the two densities, $D_2 - D_1$. The corresponding radiation intensities producing these densities are given respectively

as I_2 and I_1 , shown on the abscissa line. The contrast, $D_2 - D_1$, then is equal to the logarithmic difference of the radiation intensities or energies, $\text{Log } I_2 - \text{Log } I_1$. The slope of the straight-line portion AB of the characteristic curve $OABC$ is given as the tangent of the angle Θ it forms with the axis of the abscissa, as indicated in the figure. This tangent may be quantitatively written in an equation form as

$$\text{Tan } \Theta = \frac{D_2 - D_1}{\text{Log } I_2 - \text{Log } I_1} \quad (93)$$

where the quantity $\text{Tan } \Theta$ is known as *gamma*, which is a measure of the development contrast of a negative.

The contrast may be expressed as

$$D_2 - D_1 = \gamma \text{Log } \frac{I_2}{I_1} \quad (94)$$

in which, γ stands for the exposure gamma and is equal to $\text{Tan } \Theta$.

When the curve, in Fig. 98, is applied to development procedure, it will be noted that gamma increases uniformly from A to B as development proceeds. The slope in this region of correct exposure, i.e., from A to B , then, will increase as time of development is increased. We may plot a curve with the gamma of various exposure densities against the time of development, and use the resultant gamma-time curve as a criterion for any correct radiographic developing time. The value of gamma, thus, becomes a measure of development contrast.

Typical characteristic curves are illustrated in Fig. 103, in which various negatives exposed to identical radiation energies are developed for different time intervals. It is further shown in this curve that as development is lengthened the gamma increases in value.

We have already seen that the temperature of the developing bath affects the rate of development of the radiographic film. When the developer temperature is high the rate of development increases, and with lower temperatures the reaction rate diminishes. Compared with a normal density obtained under normal temperature for a given time of development, a film developed for the same time but at a higher temperature than the normal the

higher rate of reaction between the silver salt and the developer will give an over-development, and hence a higher contrast. If the development temperature is lower than that for normal an under-development will result. It must be noted, however, that a high temperature development is not desirable owing to the tendency of the gelatin of the emulsion to become swollen, and often forming a network of fine lines called *reticulation*.

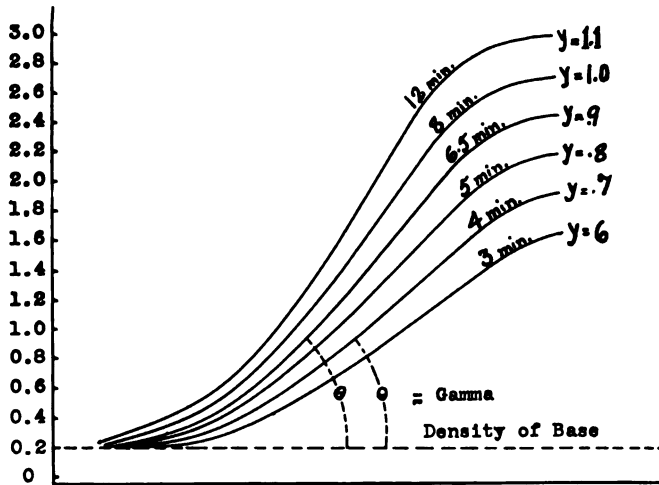


Fig. 103. Typical Characteristic Curves For Various Development Time Intervals.

Indiscriminate agitation of the developer and prolonged processing of the emulsion in it also will affect the rate of development. If this is carried too far, contrast increases excessively because the developer begins to reduce the unexposed silver bromide crystals to metallic silver, causing *developer fog* which obscures the detail definition in the radiographic image.

Fog due to the developer action on the silver grains is different for films of different emulsions. This effect further varies from one developer to another for the same type of film, and from one interval of developing time to another. The development fog increases with prolonged developing of the film.

The apparent clumping of the silver grains around the centres of the latent image causes a loss of definition similar to that produced by large crystal (fast screens) intensifying screens.

This effect, usually a mottled appearance, is referred to as *graininess*, and is inherent to some extent in every film emulsion, being a direct function of its speed. Graininess further increases with gamma and with factors that cause to prolong the development time. With fine-grain developers the graininess decreases with slight loss of developing speed.

Before leaving the subject of film characteristic, a brief discussion regarding the resolving power of a film should not appear out of place. We have already referred to sharpness as that quality of the radiograph which permits the reproduction of sharp edges at the transition boundaries of the image detail. The ability of the emulsion to record fine detail so that smallest possible degree of differences in transition between various densities of the image are clearly distinguishable is called the *resolving power* of the emulsion. This property of the emulsion is expressed quantitatively in terms of the number of lines per mm that are perceptible to the normal eye. The quality is further dependent on the degree of development of the film, and particularly on the exposure used. The resolution of a film decreases with over-contrasty or with under-exposed films.

The optimum quality of a radiographic film, then, may be summarized as consisting of properties of high speed, minimum graininess and hence high definition, high contrast, minimum fogging due to developer, and maximum available exposure latitude. It will be found, however, that no single film will possess all these characteristics. But, recent developments in radiographic film emulsions appear to be so encouraging that a modern film is not far from possessing such properties which are most desirable under the existing radiographic facilities.

5. Reduction, and Intensification, of Radiographs.—At times the radiographer finds that a certain radiograph is either too dense or too light and that the exposure cannot be repeated due to the absence of the part radiographed, or due to the impossibility in duplicating the exact position of the area of interest, or, because he does not wish to make another exposure in view of the added cost of the additional film, he may resort to processing the film in special chemical solutions to correct the trouble. When the film is too dark, he may use a reducing agent, or, if the film is too light, recourse may be had to an intensifying solution.

(a) *Reduction of Density in a Radiograph.*—In photography, the term “*reduction*” refers to the removal of some of the metallic silver grains from the emulsion of a processed film so as to produce a less dense image. A dense radiograph is over-contrasty, and the effect is due either to over-exposure or to over-development. Such a radiographic quality can be corrected to certain extent by reducing it in a clearing bath. To achieve this end, the film is wetted by immersing it in water for a few seconds, and then placed in the reducing solution until the required density is obtained. It is then taken out of the solution and washed thoroughly to remove all traces of the chemicals.

The simplest and easiest way is to use prepared reducing chemicals supplied in powder form with directions on the package. Each package is dissolved in a specific amount of water and is ready to use. But, when this is not available, a reducing solution can be prepared according to the following formulae emanated from Eastman Research Laboratories:

FARMER'S REDUCER (R-4a)

(For correcting over-exposed radiographs)

Stock Solution A

Potassium Ferricyanide	37.5 grams
Water to make	500.0 Cc

Stock Solution B

Sodium Thiosulphate (Hypo)	480.0 grams
Water to make	2000.0 Cc

For use, take:

Stock Solution A	30.0 Cc
Stock Solution B	120.0 Cc
Water to make	1000.0 Cc

(Add A to B, then add the water. Stir well.)

Pour the mixed solution at once over the radiograph to be reduced. Watch closely. The action is best seen when the solution is poured over the radiograph in a white tray. When the desired density of the radiograph is obtained, remove the film from the reducer and wash it thoroughly before drying.

Since the above reducer decomposes rapidly, the two component solutions should be mixed just previous to use.

Farmer's reducer (R-4a) also may be used as a two-solution

formula by treating the dense radiograph in the ferricyanide solution first and subsequently in the hypo or in stock solution B. This method has the advantage of giving almost proportional reduction and correction for over-development, whereas the first method (single solution) gives only cutting reduction and corrects for over-exposure.

For correcting contrasty radiographs due to over-development, the following reducer is recommended:

PROPORTIONAL REDUCER
(Formula R-5)

Stock Solution A

Water	1000.0 Cc
Potassium Permanganate	0.3 gram
Sulphuric Acid (10% solution)	16.0 Cc

Stock Solution B

Water	3000.0 Cc
Ammonium Persulphate	90.0 grams

For use, take 1 part of the stock solution A to 3 parts of the stock solution B. Mix well. Immerse the film into the solution until sufficient reduction is secured. Remove the film and wash it a few seconds in water, and then immerse it in a 1% solution of sodium bisulphite until the image is cleared. Wash the radiograph thoroughly in tap water before drying.

When radiographs are lacking brilliance due to the effect of secondary radiations or due to a high temperature development, the film may be improved by treating it in a clearing bath (Eastman Formula R-8) at 65°F. to 70°F. (18°C. to 21°C.) for 1 to 10 minutes, the time depending on the extent of clearing desired. If the effect of the secondary radiation is not pronounced, 2-minute treatment is considered to be sufficient. The films, however, should be thoroughly washed before and after clearing to remove all adherent chemicals from the emulsion.

This formula (R-8) is especially recommended for treatment of dense, contrasty radiographs. Since this reducer is the only known single solution of excellent keeping characteristics, it may be prepared in a tank of proper size and placed adjacent to the fixing bath. Films, after having been taken out from the fixer and thoroughly rinsed, may be placed in this bath, as a

KODAK REDUCER R-8

Water (at about 125°F., or 52°C.).....	625.0 Cc
Ferric Chloride, crystals.....	25.0 grams
Potassium Citrate	75.0 grams
Sodium Sulphite, desiccated.....	30.0 grams
Citric Acid.....	20.0 grams
Sodium Thiosulphate (Hypo).....	200.0 grams
Water to make.....	1000.0 Cc

routine procedure, to improve their radiographic quality. The effect of fog, over-exposure, and over-development can thus be partially remedied. If a slower action is desired, the solution may be diluted with equal volume of water.

(b)—*Intensifying Light Radiographs*.—While the need for intensifying a radiograph is seldom met in industrial radiographic work, where necessary the density of a light radiograph may be greatly improved by treatment in an intensifying solution.

The chemical process of intensification is the opposite of photographic reduction. We have already noted that a dark, contrasty radiograph is one which has an excess of silver grains in the emulsion, and therefore, the purpose of the reducer is to remove some of these grains so as to produce a less intense image. The object in the intensifying of a (light) radiograph is to increase contrast by depositing around the nuclei of the silver grains some material to make the image more opaque. This end can be achieved by the deposition of a silver, chromium, or a mercury, compound upon the image, the type of chemical to be used depending on the discretion of the photographic (or radiographic!) user.

MERCURY INTENSIFIER

(Formula In-1)

Potassium Bromide	22.5 grams
Mercuric Bromide	22.5 grams
Water to make	1000.0 Cc

The radiograph is bleached in the above solution until it is white, and then thoroughly washed to remove all traces of adherent chemicals. The emulsion is then blackened with any one of the following solutions:

- (1) A 10% sodium sulphite solution.
- (2) Developing solution (diluted 1 : 2).
- (3) 10% ammonia (1 part concentrated ammonia, 28%, to 9 parts of water).

These solutions give progressively greater density in the order given.

After the desired density is obtained, the film is washed thoroughly and set aside to dry.

If it is desired to increase contrast greatly, the bleached film may be treated in the accompanying cyanide-silver solution. This bath cuts the shadows to a slight extent, producing at the same time intensified highlights with consequent increase in contrast.

CYANIDE-SILVER SOLUTION

Sodium or Potassium Cyanide	15.0 grams
Silver Nitrate, crystals	22.5 grams
Distilled Water to make	1000.0 Cc

Dissolve the cyanide and the silver nitrate crystals separately. Add the silver nitrate solution to the cyanide solution until a permanent precipitate is just produced. Set the mixture aside for a few minutes, and then filter. The solution is ready for use. (Note:—Since cyanide is a deadly poison, care should be exercised not to allow it to come in contact with acids when discarded into the sink. Have ample water running into the sink while discarding the spent solution.)

SILVER INTENSIFIER

(Formula In-5)

Stock Solution No. 1

Silver Nitrate, crystals	60.0 grams
Distilled Water to make	1000.0 Cc

(Store in a brown bottle.)

Stock Solution No. 2

Sodium Sulphite, desiccated	60.0 grams
Water to make	1000.0 Cc

Stock Solution No. 3

Sodium Thiosulphate (Hypo)	105.0 grams
Water to make	1000.0 Cc

Stock Solution No. 4

Sodium Sulphite, desiccated	15.0 grams
Elon	24.0 grams
Water to make	1000.0 Cc

To prepare the intensifier, take

Solution No. 1 1 part

Slowly add to this

Solution No. 2 1 part

Shake or stir to obtain thorough mixing. The white precipitate which appears is re-dissolved by the addition of

Solution No. 3 1 part

Allow the resulting solution to stand a few minutes until clear. While stirring, add

Solution No. 4 3 parts

Stir the entire solution thoroughly.

When all the solutions are mixed in the order given, the intensifier is ready for use. The film should be treated immediately to avoid weakening of the intensifier. The degree of intensification to be obtained depends upon the time of treatment which should not exceed 25 minutes. The progress of the intensification may be followed visually and arrested at any stage.

After intensification, the film should be immersed in a plain 30% hypo solution and agitated constantly for 2 minutes. The film is then removed and washed thoroughly.

The mixed intensifier is stable for approximately 30 minutes at 70°F. (21°C.). To obtain the most satisfactory results, therefore, it is deemed best that the radiograph be treated within this period.

When an intensification, or, reduction, is indicated in a radiograph, it will be more expedient to give the film such a treatment immediately after it has been washed subsequent to fixing. Much time is saved, and the radiograph, when dry, will be ready for diagnosis.

Precautions:—Stains are sometimes produced during intensification or reduction of the film unless the following precautions are observed: (1) The radiograph should be fixed and washed thoroughly before treatment and should be free of scum or stain. (2) The radiograph should be hardened for 3 minutes in the formalin hardener (SH-1), rinsed, and immediately immersed for 5 minutes in a fresh acid fixing bath before the intensification or reduction treatment. (3) Only one radiograph should be handled at a time, and it should be agitated thoroughly during

the treatment. Subsequently, the radiograph should be washed thoroughly and all water droplets should be drained carefully before setting it aside to dry.

FORMALIN HARDENER

(SH-1)

Formalin (40% formaldehyde solution)	10.0 Cc
Sodium Carbonate, desiccated	5.0 grams
Water to make	1000.0 Cc

Frequently the fingers of the operator become stained during the treatment of the film. Such a stain, unless removed by chemical means, has to wear out before it disappears. When the stain is fresh (a few hours old) on the fingers, it may be removed by treatment in the following solution:

HAND STAIN REMOVER

(Formula S-5)

Solution No. 1

Potassium Permanganate	7.5 grams
Water	1000.0 Cc

Solution No. 2

Sodium Bisulphite	480.0 grams
Water to make	1000.0 Cc

Rub the hands or immerse them in a small amount of Solution No. 1 for 2 or 3 minutes. Rinse the hands in water. Then, rinse them with Solution No. 2, which will remove the stains. Repeat the treatment if necessary. Wash the hands thoroughly with soap and water.

While stains on radiographs may be treated in solutions similar to the one above, satisfactory results are seldom obtained due to a great many factors entering into the successful use of the remover.

6. Unsatisfactory Radiographs.—Most of the faults encountered in radiographs are a direct result of failure to observe instructions given for the handling of the films, their proper treatment in the respective processing solutions, and in the final process of washing and drying them. Needless waste of time and unnecessary annoyance will be avoided if practice of inadvertence is abandoned. Although human nature has a great

tendency toward attaining perfection, its equally great tendency is to overlook such matters apparently trivial to him yet in the final analysis an issue of prime importance. Pursuant to such an issue in mind that the accompanying discussions are presented partly to guide the reader and partly to indicate the general trend which still tends far from the ultimate goal.

(1) **BLURRED RADIOGRAPHIC IMAGE.**—This is primarily due to the vibration of the x-ray tube during exposure, due to faulty support. The remedy is to tighten all movable parts, and to check the transformer embodying the tube, in case the latter is oil-immersed type.

Incorrect alignment of the principal ray in respect to the area of exposure will also produce unsharpness in the image. With a given target angle, if the distance between the target and the film is such that the radiation distribution to the film is not uniform due to "heel effect," the portions of the radiographic image under the anode side of the x-ray tube will appear blurred. In the latter event, the tube should be raised to a distance whereby the radiation beam will cover the exposure field completely and uniformly. Excessively large part-film distance, large focal spot, poor contact between the film and the intensifying screens, and screen intensifying factor are some of the secondary causes of undue unsharpness in a radiographic image.

(2) **INCORRECT DENSITY.**—When the radiograph has a high density the cause may be attributed to one of over-exposure, over-development, or fog. The remedy for the first is to apply a new exposure technique, giving due consideration to the density and the thickness of the part; and, the indicating meters, especially the exposure timer, should be checked to see if they are in good operating conditions. For the second, the cause is either the time of development is exceeded above that for normal or the temperature of the developer is too high. The remedy is to consult pertinent charts and employ correct development procedure. For the cause and remedy for fog, see Caption (4).

A low density radiograph is the result of under-exposure, or under-development. The first may be corrected by applying for the next exposure standard exposure factors. Under-development may be due to one of the following causes: Too short a time of development, exhausted developer, or the developer solution is

incorrectly mixed. Removing these deficiencies will remedy the condition.

(3) **INCORRECT CONTRAST.**—A radiograph of high contrast is due to insufficient kilovoltage, that the penetration of the part is inadequate, or, it is due to over-development. The first cause may be remedied by applying standard exposure technique for the part being radiographed, while the remedy for the second will be one of employing correct development methods with due consideration to time-temperature factors.

Too low a contrast in a radiograph indicates excessive penetration due to a high voltage, or due to under-development. For the first case, consult the exposure technique charts for the next exposure, while for the second, check the temperature of the developer and apply the correct time interval.

(4) **FOG.**—There are at least three main causes for fog in a radiograph. (a) Exposure of the film to radiation of one form or another, (b) Chemical action of the processing solutions on the emulsion of the film, and (c) Overdated storage films.

Exposure of the film to disseminated radiations may be curtailed by leakage of light into the processing room, by exposure of the film to stray x-rays, and to emanations from radioactive substances. Static electric discharges formed by the friction of the film with some other object, such as the hand, cassette, lead screens, or any part of the exposure holder, will cause dendritic or filamentary black areas in the radiograph. Finger prints through careless handling of the film, and holding the film before the safelight for a prolonged time while still in the process of development are some of the other causes contributing to the impairment of the radiographic quality. The illumination from the safelight should be tested from time to time to make sure that the filter dye embodying the glass has not faded by the heating action of the safelight lamp.

When fog is due to the developer action on the emulsion of the film, the cause is due to one of over-development, incorrectly mixed developer, contaminated developer solution, or prolonged inspection of the film during development, which latter procedure causes the wet emulsion to become oxidized in contact with the air (aerial fog).

Dichroic fog is characterized by the peculiar green appearance

of the film when viewed by reflected light, and pink by transmitted light. Developing the film at higher temperature than that specified; placing the film in a fixing bath whose acid content is exhausted; or, transferring the film from the developer to the fixing bath without first thoroughly rinsing it in water, a chemical reaction between the developer on the emulsion and the dissolved silver salts occur, yielding metallic silver in the shadow portions of the radiograph where bromide is left unaffected during development. Radiographic films having fine grain are most susceptible to this type of anomaly.

Occasionally, in deep developer tanks a slimy deposit of bacteria or fungi growth occurs, and this is detected shortly after a fresh developer is placed into the tank and the resulting fogging effect indicated on the films developed in this bath. This may be explained by the fact that the action of bacteria on the sodium sulphite is one of reducing it to sodium sulphide which reacts with the silver bromide of the emulsion and reduces it to metallic silver, enhancing an over-all blackening to the film.

The deposit of fungus or bacteria may be removed by washing the tank thoroughly with a hypochlorite solution. If it is desired to retain the developer for further use, addition of a small quantity of lead acetate (1 gram per liter of the developer) to the developer will remedy the situation. A 0.2% solution of benzotriazole may be added to the developer to serve the purpose.

Contamination of the developer by hypo, sulphide from toning baths or reducers, traces of metals such as copper, tin, or iron from containers cause chemical fog, the prevention of which only depends on the removal of the cause.

Placing the cassette which has been recently cleaned with peroxide of hydrogen will produce an over-all fogging effect on the radiograph.

(5) **BROWN STAINS.**—If the procedure of rinsing the film between development and fixation is not carried out carefully, a considerable quantity of alkali from the developer retained on the film will be carried over to the acid fixing bath; and, after sufficient amount of the solution is thus transferred into the fixer, the potency of the latter will be impaired by having lost its acidity. When a film is fixed in such a solution, a brownish stain will occur in the radiograph. This may also arise from

incomplete fixation, lack of agitation of the films (when a group of films is being processed at the same time), and by prolonged development in an old, oxidized developing bath. The remedy is to omit the cause by exercising more discrimination.

(6) EXTRANEOUS DEPOSITS ON RADIOGRAPHS.—(a) *White Crystalline Deposit*.—This may appear on the radiograph several days or weeks after the film is dried. The effect is due to an incomplete washing of the film after fixation. The crystals are hypo, which may be removed by re-fixing the film in the hypo for several minutes and then washing it thoroughly.

(b) *Whitish or Pale Yellow Deposit*.—This may be due to a fine deposit of sulphur from the fixer which has been partially decomposed, or, to foreign matter dissolved in wash water and adhering to the surface of the emulsion. The film may be treated by swabbing its surface with cotton before drying.

(c) *White Amorphous Precipitate*.—Sometimes a white scum consisting of aluminum sulphite, often having a greasy appearance, occurs on the surface of the radiographic film, causing a great deal of annoyance especially when the films are dry. This may be due to insufficient rinsing of the radiograph before it is immersed in the hypo, or due to a fixing bath which has lost its acidity. It may be prevented by rinsing the film after development and by agitating it on first immersing in the fixing solution.

If the deposit has already appeared on the film, it may be removed by swabbing the film with cotton soaked with the fixing bath, or, swabbing it with 5 to 10 per cent solution of sodium carbonate, made ammoniacal with ammonium hydroxide, and by subsequent washing of the film. Since alkali dissolves aluminum sulphite, sodium carbonate which gives a mild alkaline reaction is used for this purpose very satisfactorily.

Fixing solutions containing boric acid have minimum tendency to scum formation of this character, since aluminum sulphite is less likely to precipitate out from a boric acid fixing bath.

With fixing baths containing chrome alum for hardening agent, a scum similar to above but greenish in color and composed of chromium hydroxide may precipitate on the film if an excess of the developer is retained by it when immersed in the fixer. The surface of the film may be wiped with cotton before it is dried.

It is impossible to remove this scum from the film after the latter is dry.

(7) **RETICULATION AND FRILLING OF THE FILM EMULSION.**—A grainy leather-like appearance of the radiograph caused by processing the film at temperatures higher than those recommended or by using an exhausted fixing bath is called *reticulation*. Only way to curb the repetition of the effect is to maintain a standardized temperature throughout the developing, fixing, and washing of the radiograph.

The loosening of the emulsion around the edges occurs as a result of fixing the film in a warm or exhausted bath which has also lost its hardening action. This may be further due to prolonged washing of the film at high temperatures. The condition is known as *frilling*, and there seems to be no remedy after once the emulsion has completely separated from the base. It may, however, be prevented by strict observance of time-temperature processing methods.

(8) **BLISTERS.**—When the sodium carbonate retained in the film emulsion is neutralized by the acid fixing solution, carbon dioxide gas is formed in the emulsion. The gas, in the process of escaping, raises the gelatin with a disruptive action. This causes small crater-like depressions in the emulsion which may be detected when examined by reflected light. The condition may be avoided by proper rinsing of the film before it is transferred into the fixer.

Films developed in a solution having sodium carbonate as the alkalizing medium are susceptible to blisters especially in hot weather. A developing bath containing sodium metaborate or Kodalk rather than sodium carbonate as the alkaline medium will avoid this trouble. The latter chemical, or the prepared developer containing Kodalk, may be obtained from any Eastman Kodak supply house.

(9) **CRIMPS IN A RADIOGRAPH.**—Inadvertent handling of the film may cause bends which may take the form of a half moon. The emulsion at this region where the bend has occurred will become desensitized (or, over-sensitized). When the film is processed a dark area (for over-sensitization), or, a light area (when desensitized), of the form of the bend will appear, frequently interfering with the image delineation. The remedy is

to handle the films more carefully, avoiding pressure, creasing, or buckling of the film. The condition is illustrated in Fig. 104. The letter "A" designates the defect.

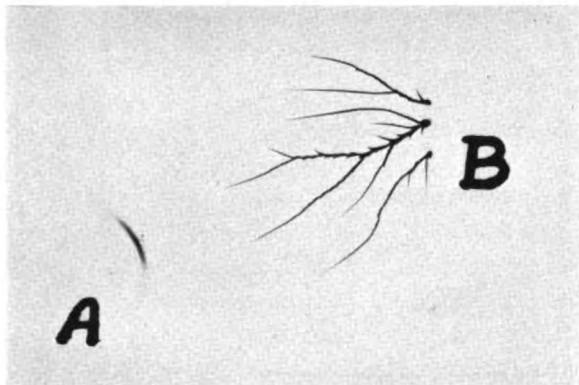


Fig. 104. (a) Crimp In a Radiograph. Over-sensitized Effect. (b) Static Discharge Effect.

(10) OIL IN THE DEVELOPER.—Mysterious shadows occurring in the processed emulsion of radiographic films have been traced to the presence of oil in the developer. Unclean containers in which the developer is mixed may be the prevailing cause. The prevention is to observe strict cleanliness in the mixing room and in the handling of the containers of the processing solutions.

(11) SILVER SULPHIDE FLAKES ON THE SURFACE OF THE FIXING BATH.—When the fixing bath, which is partially exhausted, is exposed to the air for a few days, it absorbs from it hydrogen sulphide which reacts with the silver-sodium-thiosulphate, forming silver sulphide. This has metallic appearance (hence, erroneously called by many x-ray technicians as *colloidal silver*) and occurs on the surface of the solution. It may be removed by carefully skimming it by means of a blotting paper or cheese cloth.

In case a radiograph is found stained with silver sulphide, the emulsion may be thoroughly wetted in cold water and the stain may be removed by swabbing the film with cotton soaked in the following solution prepared by the author and successfully used for this purpose in his laboratory.

SILVACOL STAIN REMOVER
(Formula SS-HM)

Sodium Perborate.....	1.5 grams
Sodium Carbonate, crystals	8.0 grams
Ammonium Hydroxide (28% solution)	6.5 Cc
Water to make	150.0 Cc
(Use the solution cold.)	

After the silver sulphide stain is removed by using the above solution, the film is rinsed thoroughly in water and immersed in a clean (uncontaminated) fixing bath for a few minutes. It is then taken out, thoroughly washed and dried.

(12) OILY APPEARANCE OF FILM SURFACE.—When the fixing solution is retained in the gelatin of the emulsion due to insufficient washing, the surface of the film will appear oily; and, when the film is dry, a white deposit will form on its surface. The film may be wetted in water, re-hypoed for several minutes, and subsequently washed thoroughly to remove all traces of the fixing bath and dried.

(13) EMULSION DEFECT.—Frequently, the surface of the film acquires granular appearance occurring in parallel lines corresponding to the corrugations of the cardboard packing of the film carton. This is caused by the exposure of the emulsion to the atmospheric moisture and its consequent deterioration. The defect is usually recognized by viewing the surface of the film by reflected light. A film of this character should be discarded.

(14) RESTRAINED DEVELOPMENT DUE TO GRAVITY.—If a radiographic film is allowed to remain stationary during a tank development, there is a tendency for the lower portion of the film to escape complete development, and, as a result, the film at this area will appear lighter.

The effect is particularly observable when two contiguous areas of the film, widely differing in radiographic density, are developed in such a position that one is above the other. The portion below the heavier density will undergo lesser development owing to the diffusing of the reaction products (especially bromides, and those having higher specific gravity) from the gelatinous emulsion downwards, restraining the action of the developer on the silver bromide. The effect is largely due to the

buffer action of the bromide ions, preventing the developer from acting normally on the exposed silver bromide.

The converse of the phenomenon will occur if the lesser density area is above the heavier density region. In either case, constant agitation of the film during development will improve the condition to a considerable extent.

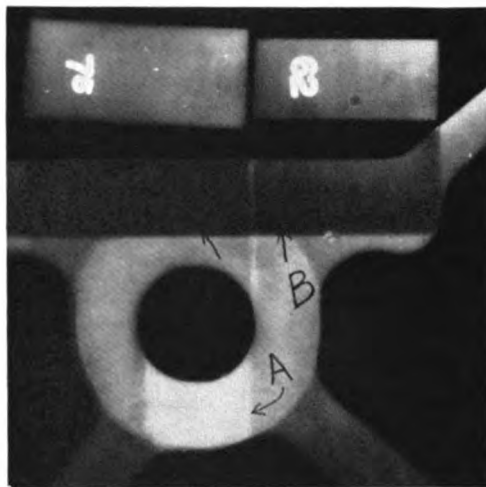


Fig. 105. The Effect of Restrained Development.

Occasionally, even with continued agitation of the film in the developing bath, there occurs a lateral diffusion of the bromide salts so that the junction between the high and low densities appears lighter. The region is known as *Markie line*. No remedy has been as yet found to prove satisfactory.

White streaks sometimes occurring where the film is attached to the upper clips of the hanger are caused by the downward diffusion of the developer products retained by the clips, preventing the further processing of the emulsion. This may be partially eliminated by removing the gelatinous matter retained between the jaws of the clips.

The removal of the gelatinous matter between the clips may be achieved by immersing the hanger into a tank filled with 25% solution of acetic acid, which will completely dissolve the gummy

material in a day or two. The hanger, then, may be taken out and washed thoroughly in water, and dried.

(15) **INCOMPLETE DEVELOPMENT.**—This is a condition arising from inadvertence and is caused by the film coming in contact with the side of the tank, with consequent failure of the emulsion to completely develop at this area. The effect may be prevented by agitating the film or the films as they are first immersed in the developer, making sure that they hang freely in the solution without making any contact with each other or with the wall of the tank.

(16) **FINGER MARKS.**—Touching the emulsion of an unexposed film with fingers contaminated with the processing solutions will produce finger marks, which may be either dark, due to the effect of the developer, or light when contaminated with the fixing bath. Droplets of the respective solutions spattering the film will respectively produce the same effect. Handling the films with clean hands and on a bench located farther away from the processing solutions will unquestionably eliminate the trouble.

(17) **SPURIOUS MARKING ON RADIOGRAPHIC FILM DUE TO METAL SCREENS.**—Not infrequently, a radiographic film in prolonged contact with metal intensifying screens (such as lead, tin, antimony, cobalt, zinc, etc.) exhibit peculiar blackened areas upon development. These markings may consist of isolated patches of dark areas, long black strips, or of an over-all heavy density similar to the effect of usual radiographic fog except that the former is more pronounced. This is particularly true where a heavy object in contact with the cardboard exposure holder exerts considerable pressure upon the film interposed between the metal intensifying screens.

Various investigators have presented their views as regards the effect of metal foils used as intensifying screens on films. One theory imputes the blackening with the presence of moisture in the intervening space between the metal foil and the film; and, another attributes the condition to the liberation of hydrogen peroxide (H_2O_2) from the metal and its further reaction with the film emulsion. It has been further shown that complete removal of moisture by the introduction of a dielectric material such as a sheet of cellophane or a specially treated moisture-absorbing paper between the film and the metal screen causes

the diminution of the effect to an important degree. Thus, from these investigations inference has been drawn that moisture rather than the particular metal used as screen is the predominating factor of the spurious effect.

Further studies of the phenomenon by the author in his laboratory have indicated that when lead, tin, or antimony (or, any other screen metal) is in contact with the silver bromide of the emulsion, the unlike metals give rise to an electrochemical reaction which is highly favored in a moist atmosphere, as the latter offers a medium of excellent electrical conductivity. As a result, the silver halide of the emulsion is partially reduced to metallic silver, which effect renders the unaffected silver bromide grains in the contiguous areas to become highly amenable to the reducing action of the developer. In short, the author condemns the theories advanced regarding the liberation of hydrogen peroxide from the metal screens or the direct action of moisture on the emulsion when enclosed in the exposure holder.

A partial remedy to the blackening of the film due to metal screens will be to impregnate the highly polished (scratchless and clean) surface of the metal screen with a radiotransparent material such as a thin coating of lacquer, varnish, shellac, or paraffin. Of these, the first is found more preferable because of its reasonably high dielectric property, its endurance life, and of the ease with which it is applied to the surface and handled during loading and unloading of the exposure holder.

(18) **REVERSAL OF THE RADIOGRAPHIC IMAGE.**—Extreme over-exposure to x-ray radiation, or, the exposure of the film to an unsafe light during development, may cause the complete or partial change of the negative to a positive image. A radiograph of this character will be of little or no value, and should be discarded. No remedy is recommended, except to remove the cause.

7. Trouble With Processing Solutions.—The useful life of a developer is dependent on the rate of oxidation of the developing agent and of the sodium sulphite present. If a developer is prepared with water which is boiled to drive off all dissolved air and then stored in hermetically sealed bottles the solution will keep almost indefinitely. In the absence of oxygen or air the life of the developer will be greatly lengthened, and, conversely,

in the presence of oxygen or air the potency of the developer will be curtailed in direct proportion to the amount of oxygen absorbed by it. Hence, the importance of covering the tank of a developing bath cannot be readily overlooked.

Of the various factors which influence the useful life of a processing solution, such as whether the solution is used continuously or intermittently, the character of the chemicals present, and the temperature at which the solution is maintained throughout its functioning life, it appears that the commonest cause for the diminution of the solution strength is the negligence to cover the tank retaining the solution when not in use. As much as two-fifths of the developer life may be curtailed due to aerial oxidation within a week if in the meantime the solution is used intermittently and steadily, the degree of exhaustion being directly dependent on the atmospheric conditions in the dark room.

With proper use, the strength of the developing solution is reduced as a result of the approaching of the chemical reactions between the developing agents and the silver bromide and oxygen from the air to a completion. This diminution in strength is further supplemented by the accumulation of the by-products such as sodium bromide, sodium iodide, and oxidation products from elon (metol), hydroquinone, and sodium sulphite, all of which exert a restraining action on the development. Thus, it is not possible to obtain adequate development from an old exhausted bath.

In the case of a fixing bath, the main fixing agent is the hypo or sodium thiosulphate, in conjunction with sodium sulphite which serves as a preservative by preventing the decomposition of the hypo. The presence of an acid, such as acetic acid or sulphuric acid, is to neutralize the alkali usually carried over in the film emulsion from the developer. A hardening agent such as potassium alum or chromium alum completes the useful purpose of the fixer. Some fixing baths, especially those which contain acetic acid, carry, in addition, a small amount of boric acid to increase the hardening life of the solution. The latter ingredient further reduces the tendency of the formation of a sludge of aluminum sulphite.

A fixing bath of optimum quality should render a rapid rate

of fixation, adequate hardening properties, and a minimum tendency to sludge during its entire useful life. Too much hardening action in the fixer may cause brittleness of the emulsion, and an insufficient quantity of the salt in the solution may cause frilling or reticulation. Normal hardening is based on 180°F. to 200°F.; that is, a film fixed in a solution having normal amount of hardener and washed in water will just start to loosen from the cellulose base when immersed in water at the above temperature. Furthermore, a properly mixed fixing bath should not form sludging if used at the proper temperature of 65°F. to 70°F. Higher temperatures not only tend to cause sludging but also effect precipitation of sulphur from sodium thiosulphate. This is characterized by the milky appearance of the fixing bath.

(a) *Faults Arising From Developer.*—A properly mixed developer is colorless. But, if it becomes colored during or shortly after mixing, faulty mixing is indicated. The solution is apt to fog the film, and if this is the case, the bath should be discarded and a new batch should be prepared.

An excess of sulphite in the developing bath, or the contamination of the latter with hypo, sulphide fumes, or ammonia, will produce dichroic fog (See:—Section 6, Chapter VII). The condition may be remedied by removing the cause.

The precipitation of a white sludge in the developer may be elon (metol) which has not been completely dissolved in the solution. The cause is either the addition of too much elon or an insufficient amount of sodium carbonate is present in the solution. In the latter event, addition of a small quantity of sodium carbonate will redissolve the precipitate. No harm will occur if too much elon has been added, as it will not go into solution to effect a chemical reaction.

In case the developer is found not to develop, the cause may be the omission of either the developing agent or sodium carbonate. The solution may be tested for alkalinity, and in accordance the corresponding chemical may be added as prescribed by the particular formula.

(b) *Faults Arising From Fixing Bath.*—A fixing bath which has been properly mixed usually does not present any fault throughout the effective life of the solution. But, any omission

or substitution due to cost of the chemicals is a grave blunder, as considerable trouble, annoyance, and money will be saved in the long run if the initial considerations of economy are not taken into account. The fine quality of radiographs obtained by use of good quality, dependable chemicals will more than offset the initial cost and sacrifice of time spent for careful preparation of the solutions. Some of the successes attained in the radiographic quality at the Aircraft X-Ray Laboratories, with which the writer is consolidated, are directly attributable to the policy of the firm to use only high quality and time-tested processing chemicals for processing thousands of films monthly.

It has been already noted that a sludge of aluminum sulphite will form if the fixing bath does not contain sufficient amount of proper acid. In this respect, further attention should be directed to the fact that if the acid content of the fixer is too high, again adverse conditions arising from the precipitation of sulphur will occur. Such a bath will be useless, and should be discarded. However, with fixing solutions containing boric acid the sludging not only will be minimized but may not even occur throughout the effective life of the bath. When the latter preparation is in effect, the bath does not need to be changed until considerable retardation of the rate of fixation is in view.

Occasionally the fixing bath acquires a milky color, and this is accompanied by a slow rate of fixation. This is due to the precipitation of sulphur because of either excess acidity of the bath or of the use of insufficient amount of sodium sulphite. It may also be due to the use of a chemically impure sodium thiosulphate. The precipitation may further be effected by temperatures exceeding 85°F. The remedy is to discard the solution and refill the tank with fresh and clear bath.

The presence of too little hardener and insufficient acidity may cause the sludging of aluminum sulphite, which will appear on the surface of the processed film as gelatinous white precipitate. Unless the films are properly rinsed in water before they are transferred into the fixer, no matter how accurately a fixing bath is prepared, a sludge of aluminum sulphite will form as a result of the neutralization of the acidity of the fixer by the action of the developer carried over. With proper proc-

essing technique, no sludging should occur with a correctly mixed fixing bath.

Inferior quality alum, presence of too much acid or sulphite, or when the alum content of the bath is very low, the emulsion of the film will not be hardened adequately. With a boric acid-alum fixer, the hardening property of the bath increases with increase of boric acid and acetic acid. But, with further increase of acetic acid the hardening qualities of the solution falls rapidly, with the resultant precipitation of sulphur.

When a white scum consisting of aluminum sulphite is found adhering to the surface of the films after fixation, the trouble may be remedied by swabbing the film with the fixing bath or with a 5 to 10 per cent solution of sodium carbonate. The films after this treatment should be thoroughly washed before they are hung to dry.

8. Recovery of Silver From Exhausted Fixing Baths.—

As has been pointed out in previous discussions, a fixing bath becomes exhausted because it is saturated with silver salts, the silver usually being in complex combination with sodium thio-sulphate. There have been various methods devised to recover the silver from an exhausted hypo, and of these the most economical (provided that volumes in excess of 10 gallons per week are discarded) method is the precipitation of the silver with sodium sulphide used in an alkaline solution of the exhausted hypo bath. The procedure may be given as follows:

Two 50-gallon water-tight barrels are provided with their inside painted with a lacquer or Kodacoat paint. One of these barrels contains the discarded fixing bath, and the other is used for precipitation of the silver. Both of the barrels are placed out of doors away from the processing room, as sulphide fumes liberated during the precipitation will readily affect the sensitive emulsion of the x-ray films.

When the first barrel is filled with exhausted fixer, the acidity of the solution is tested either with a blue litmus paper or by titration.

The solutions for precipitation are prepared as follows:

Solution No. 1

Sodium Hydroxide	2 pounds
Water to make	1 gallon

Solution No. 2

Sodium Sulphide	2 pounds
Water to make	1 gallon

When the solutions are prepared, they are stored away from the dark room to prevent the fogging of the films.

Fill the second barrel with about 40 gallons of the exhausted fixer from the first barrel. Add 1 ounce of *Solution No. 1* to each gallon of fixer. Stir well, and test with the litmus paper. Add more, if necessary, until the fixer becomes alkaline, as indicated by the blue color of the litmus paper. To the alkaline fixer mix 8 additional ounces of the *Solution No. 1* to produce an excess alkalinity.

To the alkaline fixing bath, add 40 ounces of *Solution No. 2*, while stirring the hypo vigorously. This produces a black precipitate of silver sulphide in suspension in the hypo solution. Let it stand for about one-half hour, and test the supernatant liquid, taken from the top of the barrel, with a small amount of sodium sulphide. If any precipitate forms, add 10 ounces more of the *Solution No. 2*, and stir well. Allow the batch to remain overnight. Drain off the clear solution by means of a syphon and discard it into the sewer. The sludge at the bottom of the barrel contains about 80 to 85 per cent silver sulphide with an excess of free sulphur. This may be either removed from the barrel, or a second batch may be prepared right on top of this sludge. The total mass, then, is removed and dried on a filter placed in the sun. When it is dry, the silver is recovered by refinery process.

Another practical method for recovering silver from exhausted hypo bath is by use of sodium hydrosulphite. The precipitating agent is prepared by mixing equal quantities of sodium sulphite and sodium hydrosulphite and adding the resulting mixture to the hypo bath to precipitate metallic silver from the bath. The procedure is as follows:

Weigh out:

Sodium Sulphite, Desiccated	40 ounces
Sodium Hydrosulphite	40 ounces

Triturate the two chemicals together into a fine mixture, and add the entire mixture to 40 gallons of exhausted hypo placed

in barrel No. 2, carefully stirring the solution while pouring the chemicals into the barrel. When a thorough mixing is effected, the treated bath is allowed to remain overnight. The precipitate, then, is decanted by syphoning the clear liquid from the top, and dried as usual. This sludge, which contains about 85 per cent metallic silver and a few per cent of free sulphur, is sent to the refiner for further purification.

When desired, the strength of an exhausted fixing bath may be restored by desilvering, and subsequently modifying the composition of the bath to prolong its useful life. The procedure is extremely intricate, and unless one is well acquainted with the chemical processes and reactions involved in the reviving of the bath, no attempt should be made to re-use the hypo after the revival of the bath through use of uncertain chemicals or procedures, as fogging of the film will inevitably result from indiscreet mixing of the various chemicals in the treatment of the hypo bath.

A satisfactory method in reviving an exhausted fixing bath, which has emanated from the author's laboratory endeavor, consists of the determination of the silver content of the spent hypo solution, adding an equivalent weight of ammonium sulphide, and subsequently determining the acidity or p^H value of the resultant solution to revive its acidity to normal concentration. A small amount of sodium sulphite dependent on the requirement of the solution is added to prevent the decomposition of sulphur during the addition of the acid to the bath. Further consideration is also given to the boric acid and alum requirements or to the equivalent ingredients. The resultant bath is crystal clear with a tinge of pale yellow, and, when the procedure is carried out accurately, possesses almost the same degree of potency as the original bath.

9. Storage of Radiographic Films.—Storage of unexposed x-ray films should be at the greatest practical distance from disseminations of x-ray or gamma radiations. If the films are kept in vaults adjacent to the radiation room, the walls of the vault should be lined with sheet lead of about 1/8 to 1/4 inch in thickness, depending upon the magnitude of stray radiation that may be expected at the location. An equivalent thickness of concrete wall will also answer the purpose. Inadequate protection from such radiations may be detected on the processed film

by the light image of a narrow band of lead foil embodied in each carton containing the unexposed films.

Heat, humidity, escaping fumes from nearby chemicals, such as ammonia, hydrogen peroxide, illuminating gas, hydrogen sulphide, mercury, and many volatile materials will have deleterious effect on the sensitive emulsion of the film. Therefore, it is desirable that the storage room be kept free of these materials, and, furthermore, it be retained cool (about 15°C. to 20°C.) and dry.

While with the old type films whose emulsion base consisted of cellulose nitrate and presented the hazard of fire when exposed to heat or open flame, the new safety base embodying the present x-ray films (and other photographic films!) is of cellulose acetate. The latter, when in storage, presents no greater hazard than would an equal quantity of newspaper in the same form. According to a report by the Underwriters' Laboratories, Inc., with reference to safety base x-ray films, "Hazards of this slow-burning film when in use are judged to be small, and, in storage, somewhat less than would be presented by common newsprint paper in the same form and quantity." This property of the safety base film should give sufficient assurance to the user that he may go about his work with confidence and ease of mind. It may further aid him in facilitating the fire insurance problems involving his x-ray laboratory.

10. Processing - Room Considerations. — For expeditious manipulation of the exposed films it appears desirable that the processing room be of ample size and that it be preferably located near the exposure room. If space permits access should be by a light-lock, or, an inside lock should be provided to prevent the opening of the door by any person from the outside while the unexposed films are being handled in the room.

It will be advisable that the processing tanks be isolated from the bench which serves the purpose of loading and unloading the exposure holders, cutting unexposed films, fastening films to the film hangers, etc. This bench should be situated preferably on the opposite side from the processing tanks to avoid the risk of inadvertently wetting the films, intensifying screens, or exposure holders.

Located on one side and underneath the bench, provision of a

bin must be made for storing a supply of films; and, on the other side of the bench nearest to the film wash tank, there should be a film-drying cabinet, which may be either of gas-heated type or one that is electrically operated with a centrifugal fan blower and a heater mounted on top of the cabinet for rapid and uniform drying of the films without overheating. On the wall, above the bench, there should be convenient facilities for keeping film hangers of different sizes, and a safelight either suspended from the ceiling or from the wall to illuminate the top of the bench.



Fig. 106. Kodak Dark-Room Lamp.

Particular convenience is afforded by the incorporation of a film-transferring cabinet in the wall between the loading bench and the radiographic room. This cabinet has usually a safety lock mechanism so that it cannot be opened from either side while the door at the opposite side is open, thus preventing light or x-radiations that may enter the dark room by way of the cabinet compartment.

It is, indeed, very essential that the processing room be absolutely light-tight, which condition instigates the necessity of a constant circulation of fresh air in the room. This end may be achieved by the installation of an air-conditioning system. If economy is of concern, a more conservative but an effective alternative is to install a motor-driven ventilator, shown in Fig. 107, which has a light-trapped inlet and an outlet, through the wall common to the ventilated room. Or, an electric blower of convenient size may be mounted in the ceiling to draw the contaminated air through a conduit to the roof. The inlet for fresh air may be located in the wall near the sink and opening to the outside. Care should be exercised that the size of the inlet aperture is at least equal to and preferably greater than that of the blower outlet.

In the attainment of the most satisfactory radiographic processing conditions, observance of scrupulous cleanliness is of

first importance. This includes the washing of the hangers, and thermometers, immediately after use, and thoroughly wiping the top of the bench and cleaning the floor before leaving the room. The procedure not only aids the prevention of the contamination of the processing solutions, and soiling of the films during handling, but also promotes in the room hygienic conditions so important for the health and well-being of the individual occupying the room throughout the day.

Dry films are more sensitive to light than when they are wet. Therefore, this will necessitate the provision of an indirect illumination of photographically safe quality to permit the manipu-

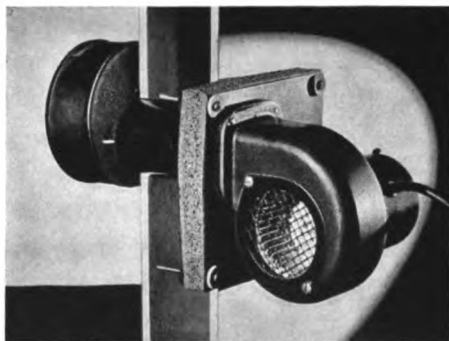


Fig. 107. Motor-Driven Light-Tight Ventilator.

lation of the unexposed films with safety. Such an illumination should be of pleasing tone so that the eyes can easily adapt themselves. One type of safelight lamp is shown in Fig. 106, which is manufactured by the Eastman Kodak Company. Wratten Safelight Series 6A provides the maximum illumination with minimum danger of fogging the film, if indiscriminately exposed to the radiation.

The safety of the illumination from a safelight can be checked by partially exposing a film about 4 square inches in diameter, or, a dental x-ray film, for varying lengths of time from a position near the loading bench where the films are usually handled. The illumination may be considered safe if no definite fog is indicated on the exposed portion after development.

It has been stated in a foregoing discussion that as the gelatinous emulsion of the radiographic film becomes soft under warm processing conditions, it will be advisable to incorporate around

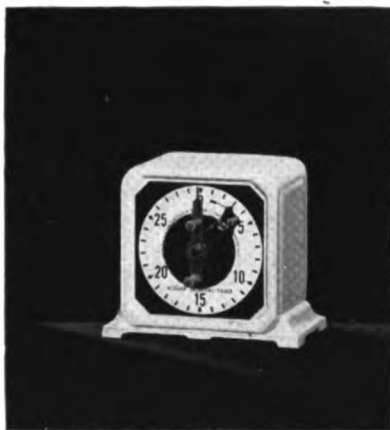


Fig. 108. Kodak Interval Timer.

the tanks containing the processing solutions an automatic temperature controlling system. The installation operates from the ordinary electric circuit, is quiet with no exposed moving parts,



Fig. 109. Eastman X-Ray Film Corner Cutter.

and further keeps the wash water at a low temperature, too. A temperature of between 60°F. to 70°F. for washing the films is considered safe. If the water is slightly at a higher tempera-

ture, the film may be washed for 15 minutes instead of the usual 25-minute period.

Assuming that the radiograph is continually exposed to fresh water, it will give up one-half its hypo content within the first 15 seconds. After a 30-second time interval, one-half of the remainder of the hypo will be removed; and, after 45 seconds one-

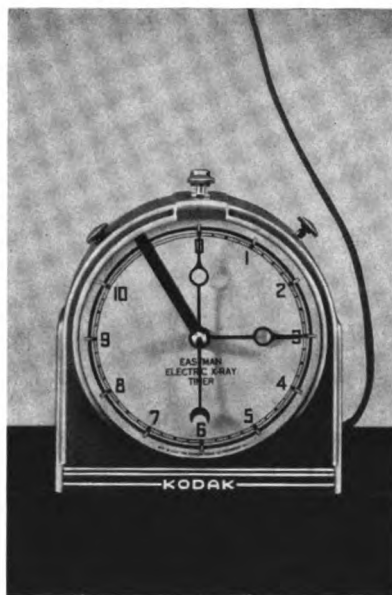


Fig. 110. Eastman X-Ray Timer.

half of the last remainder will be removed, and so on. Thus, at the end of 1 minute, one-sixteenth of the original hypo will remain in the emulsion. Whereas, when a radiograph is washed in the usual manner in a washing tank, it will give up half its hypo within 25 to 30 seconds.

It will be thus noted that the rate of washing is a direct function of the degree of agitation and of the rate of removal of the wash water. If the hourly flow of fresh water is 10 times the capacity of the tank, 15 minutes of washing will be sufficient to clear the film of its hypo. If the rate of flow is halved, the washing time must be doubled.

For further convenience, a 14" x 17" fluorescent illuminator,

Fig. 124, may be mounted in the wall right above the wash water tank. This aids the inspection of the processed films for correct exposure technique or for correct view of the specimens radiographed. The illumination in the dark room may be further supplemented by a white light in the ceiling, and which may be turned on and off from a switch near the entrance door to the dark room. The latter switch can be so designed that when the white light is turned off it automatically turns on a red light which may be placed outside the dark room above the entrance door, giving notice that the processing room is in operation and persons desiring to enter should exercise caution by not letting any light through the entrance door.

CHAPTER VIII

DIAGNOSIS OF RADIOGRAPHS

As has already been fully discussed in Chapter VI, the application of x-rays to the examination of materials of industry lends itself to the purpose of exploration and detection of inherent discontinuities or extraneous entities internal to the structure, and further, through disclosure of evidence by this inspection to assist the producer to improve the quality of his product by developing new manufacturing methods in an effort to produce materials that are sound and dependable from a technical viewpoint. Though the examination has been particularly restricted to the inspection of metal castings, and welds, and occasionally of forgings and rolled metals, radiography has further gained prominence in the realms of plastics, assemblies, molded products, textiles, synthetic derivatives from coal, wood, fruit industry, and lately in the field of art. The very advantage of such an investigation resides in the fortunate fact that the revelation of any gross imperfection is provided by non-destructive testing, whereby the material under consideration remains intact, same as before the radiographic examination.

The question of what types of parts should be x-rayed, and why, will depend mainly on the structural importance of the material, its functional use, and on the method of producing it. The factor of ultimate load stress requirements, the amount of machining necessary and the stress conditions under which it is to be performed, and by reason of compliance with certain specifications set forth by pertinent authorities, appear to bear considerable weight on the issuance of a conclusion.

It is to be further remembered that through x-ray control of foundry procedures more homogeneous structures with greater uniformity in the quality of the casting is insured. This results not only in the increase of production rate but also in the improvement in the design of bulky parts through curtailment of a reduction in the dead weight with resultant increase in strength of the material and in usable space so valuable in aerial navigation. Furthermore, by the discrimination of defective parts at

the founding or fabricating source the hazard of failure is minimized and the endurance life of the structure is materially extended.

Among various important applications of x-rays resides their adoption, in the aircraft industry, to routine inspection of various structures on whose character of performance and mechanical conditions depends the safety of life, and where economy particularly due to machining costs is an essential problem. Intermittent inspection of parts of lower ultimate stress load requirements are also performed, and if any rejections occur additional x-raying up to 100% is made depending on the character of imperfections disclosed by the rejected parts.

1. Radiographic Diagnosis of Castings.—In the foregoing discussions it was noted that a radiograph is a shadow representation of the different densities and thicknesses of a part traversed by x-rays. The processed film consists of light and dark areas corresponding respectively to regions of lower penetration and to areas of higher penetration. A section of a part which is thin will permit more of the x-ray radiation to pass through and thereby to produce greater blackening in the film which absorbs this radiation. Similarly, a section having a relatively large thickness will absorb relatively greater amount of the incident radiation energy with the result that the emergent radiation, whose intensity will be diminished by its passage through the part, will produce blackening to a lesser degree.

From above inferences it will be evident then that voids, cavities, or other discontinuities in metals of uniform density will be recorded on the film as dark regions, whereas inclusions of higher density than the base metal will be indicated as lighter areas on the radiographic film. Specimens containing inclusions having densities lower than the base metal will be more transparent to x-rays, and, therefore, darkening will result in the film corresponding to these regions of inhomogeneity. Excess metal on the surface of the specimen will appear as a light region, and the absence of metal such as surface pits, scratches, and depressions will register as darkened areas.

In the radiography of castings, the character of suspicious markings which may appear on the radiograph should be first determined as to whether the condition is inherent in the casting

examined or it is attributable to faults arising from defective film emulsion or faulty processing. It is, therefore, very essential that these markings or patterns be accurately recognized and discriminated in favor of one or the other condition. All surface irregularities of the casting should be carefully observed and compared with the corresponding patterns indicated in the radiograph precedent to an attempt to identify the discontinuities internal to the metal and to arriving at any conclusion as to the disposition of the part.

The internal discontinuities of a casting may be classified into three types in accordance with the location and the magnitude of the flaw, and with the role it will play in rendering a harmful effect to the casting. This may be summarized as: (A) Defects whose concentration in the section specified may produce certain localized stress conditions, causing the failure of the part to properly function. These are cracks, macroshrinkage, pipes, hot tears, ruptures, cold shuts, and misruns. (B) Defects that generally are not serious but in view of the character of their alignment in a section of structural importance and function may cause possible stress concentrations, and may be recognized as microshrinkage, gas cavities in linear formation, segregation, mottling, and sometimes dross. (C) Those defects that generally produce no localized internal stresses, and the character of their undesirability in the casting will be determined by the magnitude of the defect and its localization. They are gas cavities, gas porosity, inclusion, microshrinkage, segregation, oxidation, mottling, surface pits, and inverse segregation.

(1) **CRACKS.**—One of the more serious defects in metal castings is a crack, which is due to the unequal cooling of a section of a molten metal during the interim of solidification. In an improperly designed casting having parts of different dimensions and possibly of wide variation of thicknesses, during solidification from a molten state, the outer dimensions adjacent to the mold and those sections that have relatively small thicknesses will solidify first. Thus, the thicker sections will cool at a lower rate and more gradually. Furthermore, a metal of given dimension at molten state will reduce in volume when solidified. This reduction is known as *shrinkage*, and not infrequently may give rise to *cracks*.

During the process of cooling, unequal cooling rates in any two or more adjoining sections having wide variations in thicknesses will result in *internal stresses*, which may cause internal shrinkage cracks in the casting. This is attributable to the more rapid cooling of the thinner section and its consequent tearing itself away from the heavier and slow cooling section, causing the formation of a discontinuity at the junction where the two sections meet. The magnitude and the extent of this discontinuity, or crack, depends on the relative thicknesses and the temperature gradients of the two contiguous sections, and further on the character of the material. The remedy is to alter the design of the mold, gates, and the risers.

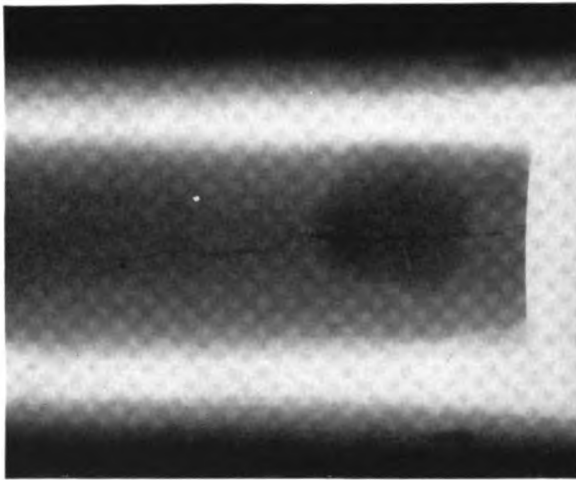


Fig. 111. A Typical Crack in Cast Magnesium Cylinder.

In a radiograph, a crack will appear as a dark line or region varying from filamentary to irregular dimensions when derived from shrinkage stresses or from insufficient feeding of the melt in cooling. When cracks originate from residual internal stresses in solid metal they have more definite directions and are more linear and of more constant width.

Cracks usually will occur near a thin fillet, adjacent the junction where a thin section joins a boss (a thick section), at the base of a light rib continuous from a heavy section, and, in the rim of a

cast wheel they usually occur extending radially, though circumferential cracks are not uncommon.

A defect of this type will seldom escape rejection when proper diagnosis is performed; and, when considered as acceptable, it will be in view of its location in the casting. For instance, if the crack is so superficial that machining will remove it completely, or if it is located in a section such as the web of a casting where the complete loss of the metal or the presence of a void will not in any manner prove injurious to the adequate functioning of the part, the latter is acceptable. But, the arrival at such a conclusion requires the knowledge of a well-trained diagnostician.

A typical crack in conjunction with a large blow-hole in magnesium sand-casting is illustrated in Fig. 111. Portions of other smaller gas-holes are shown on either side of the reproduction.

(2) **MACROSHRINKAGE.**—During the process of solidification, the metal next to the mold will be the first to cool, thus solidifying to form a solid crust or shell. The process will move gradually inward and toward the core of the molten metal, increasing the thickness of the solid shell. In the interim, the total volume of the casting will reduce by contraction, and at the same time drawing metal from the center section at elevated temperature. At the time this contraction occurs, the pasty melt gives way to the pull exerted by the more solid adjoining walls. The result is a fine rupture of the metal at this point, and is technically referred to as *macroshrink*. Too high a pouring temperature will cause this type of shrinkage. Therefore, the design of the mold and its auxiliaries should be such that cooling will be effected more gradually and evenly.

Macroshrinkage may be recognized in a radiograph by the peculiar occurrence of dark regions generally of dendritic or filamentary character and having irregular dimensions. The outlines are more or less indistinctly delineated. This defect may occur almost in any region of the casting, depending on the pouring temperature, designing of the gates and the risers, and most important of all on the magnitude of the molten metal supplied to the particular section wherein the shrink has occurred. The extent of the shrinkage is usually determined by the magnitude of the radiographic contrast indicated at the region of occurrence. This is a serious defect, and should be rejected in accordance with due

consideration given to its localization, magnitude, and the functional character of the casting. An aluminum casting which has been rejected by the diagnostician is shown in Fig. 112.

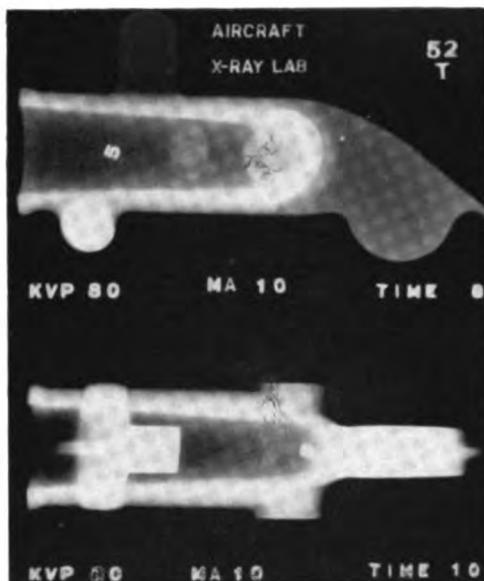


Fig. 112. Macroshrink in an Aluminum Sand-Casting.

(3) PIPE.—It is a cavity, usually filamentary, formed in the casting during its transition from a liquid phase to the solid state. The defect generally occurs in that portion of the melt that solidifies the last. Consequently, the condition results in the contraction of this section, causing the cavity or the pipe. An effective method to eliminate piping in the founding process is to retain a reservoir of liquid metal above the specimen to continuously supply the reduction of the molten metal by shrinkage.

In a radiograph, pipes are represented by filamentary dark lines, occasionally discontinuous, and practically all running in the same direction. Some pipes appear to be a network of hair-line cavities, but this is owing to the superimposition of several layers of the defect which may be extending to various directions. Dependent on the dimensions, magnitude, and location, the presence of pipes in a casting presents a serious problem which generally

necessitates the rejection of the casting.

(4) **HOT TEARS.**—The radiographic images of hot tears and pipes are quite similar and frequently cause uncertainty and confusion as to their discrimination. Hot tears are ruptures caused when the casting is deformed or disturbed while still in plastic state. This can be remedied to a large extent by allowing the molten metal to completely solidify before it is taken out of the mold.

Hot tears have defect properties quite akin to cracks and ruptures, and should be treated accordingly during radiographic diagnosis.

(5) **RUPTURE.**—This is a defect bearing identical appearance in a radiograph as those presented by hot tears, cracks, and pipes. The accurate identity will be based on the location of occurrence, surface indications, and on the nature of the casting. Frequently, ruptures are visible on the surface of the casting, and dispositions may be made without recourse to radiographic findings.

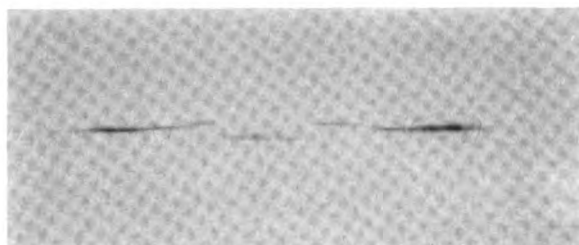


Fig. 113. Radiograph Showing Pipes and Ruptures in a Steel Casting.

(6) **COLD SHUT.**—A cold shut is produced by the failure of the union of two or more streams of molten metal flowing from different directions as a result of interrupted pouring. Further cause is attributable to the solidification of one surface before the adjoining melt flows over and unites with it. The surfaces of contact are generally oxidized, and this may be often detected by visual inspection. To eliminate the cause, the casting operation should be carefully performed with due consideration given not only to placing the gates and the risers at proper locations of the mold but to the pouring temperature and the maintenance of this

temperature long enough for the molten surfaces of the flowing metal to unite.

Radiographically, a cold shut, shown in Fig. 114, is represented

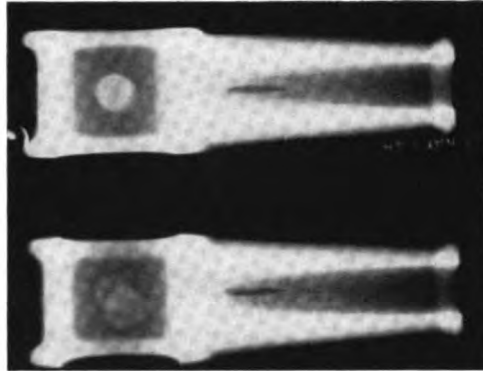


Fig. 114. A Cold Shut in Aluminum Casting.

by a distinct line or lines of demarkation which sometimes reveal distinct contiguous areas of various radiographic densities.

(7) MISRUNS.—Misruns, usually detectable on the surface by



Fig. 115. A Misrun in a Magnesium Sand Casting.

visual examination, occur as a result of failure of the molten metal to fill the section of a casting, thus leaving the region void. Feeding of ample metal at the proper temperature through the gates

will obviate the repetition. In the radiograph, it appears as a prominent area of smooth outline, and having variable dimensions producing high density and contrasty image.

(8) GAS CAVITIES.—A gas cavity, also known as a blow-hole, is produced as a result of trapped air, gases liberated from the mold, from the molten metal, etc., and their failure to escape during the solidification of the metal. These gases tend to become localized on the cope side of the metal casting. Low rate of transition process from liquid to solid state will permit, for the most part, the escape of these gases.

A blow-hole or a gas-hole is represented in the radiograph as well-defined dark area of spherical or oval shape. In die-cast, or extruded, materials a gas-hole will appear flattened and elongated

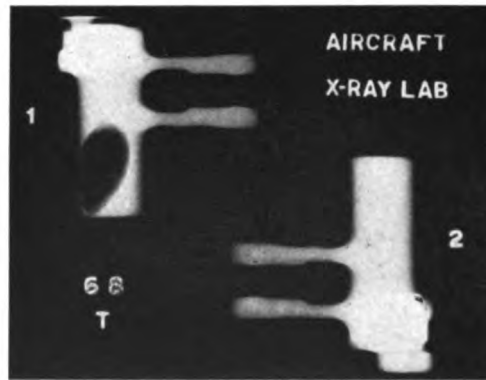


Fig. 116. A Gas-Pocket in an Aluminum Casting.

due to the pressure exerted by the surrounding metal whereby the normal spherical shape becomes deformed in accordance with the extent and direction of the exertion.

Occasionally, a gas-hole becomes so extended that it appears like a narrow dark line and it is frequently mistaken for a shrink or for a small rupture. A distinguishing difference resides in the rounded contours of the extremities of the gas-hole, whereas those of the shrink would occur as sharp and pointed segments. The gas pocket may further take the form of a tear drop, in which event one end is large and rounded while the other is attenuated to a point. Gas-holes may occur singly or in a group, in which

latter case the rejection of the specimen appears to be a certainty.

(9) GAS POROSITY.—Porosity, when present, is usually characteristic to a rapidly cooled casting. When the metal solidifies at a high rate, the gases which are entrapped by turbulence during the process of pouring and those evolved from the molten metal are not allowed sufficient time for their escape from the casting. In aluminum alloy castings, porosity due to dissolved hydrogen

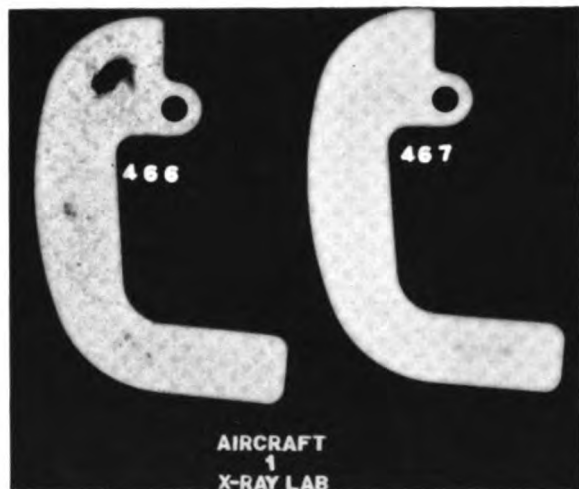


Fig. 117. Left, Excessive Porosity in Aluminum Die-Casting; and, Right, Sound Casting of the Same Material.

in the molten metal occurs well distributed throughout the specimen especially in thin sections. The treatment of molten aluminum with atomic chlorine will remove most of the gases that have been dissolved during the casting process.

The solution of gases in the molten metal increases with rise of temperature, indicating that the process is endothermic. Therefore, castings are generally poured at the lowest temperature consistent with the plastic properties of the metal. If the cooling is gradual and at a low rate, the dissolved gases escape as bubbles as long as the metal is maintained at a liquid state. Porous molds, such as sand molds and plaster of Paris molds, greatly facilitate the removal of the gases from the cooling melt.

In the radiograph, gas porosity will be indicated as round or irregular dark spots, whose sizes vary with the gas content of the

metal, and is further dependent on the rate of solidification—the faster the cooling relatively greater amount of porosity is produced. The shapes of these minute dark spots tend to be elongated, and with a casting having coarse grain structure they may assume curved forms. Great attention should be directed to the radiographic interpretation so that the peppering effect of porosity due to gas is not confused with microshrinkage, whose radiographic appearance is closely related to gas porosity.

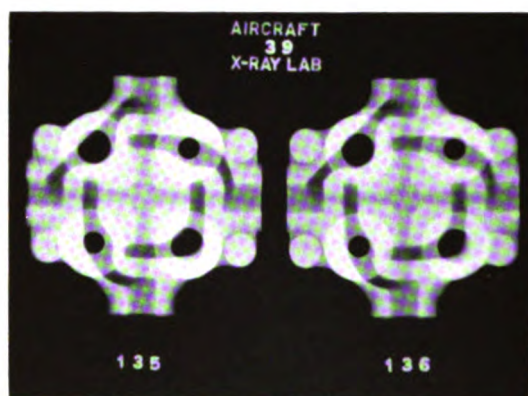


Fig. 118. Radiograph Illustrating a Perfect Foundry Procedure Combined with Excellent Radiographic Technique.

(10) INCLUSIONS.—For sake of convenience and of clarity of conception, inclusions may be classified into two main types according to their differences of x-ray absorption coefficients relative to the base metal. These are: (a) Inclusions having densities greater than that of the base metal, and (b) Inclusions having densities smaller than the base metal.

(a) *Inclusions of Higher Density Than Base Metal.*—Inclusions of particles of iron, zinc, lead, etc., or any other metal of high atomic number, when mixed inadvertently with the molten aluminum, or magnesium, or the alloys of either of these latter metals, will appear as white spots or as irregular areas in the radiograph, since the metals first mentioned have higher densities than aluminum or magnesium. Such an inclusion may be a chipped-off particle from the metal mold, or it may be carried into the

melt by sweepings from edges of the melting pot. Or, still further, the included metal may have been carried off adherent to the surface of the ingot. Rejection of the castings containing such defects depends on the machining facilities (as the edge of a tool used in machining aluminum may break when it encounters relatively harder metal), and on tests based on static analysis.

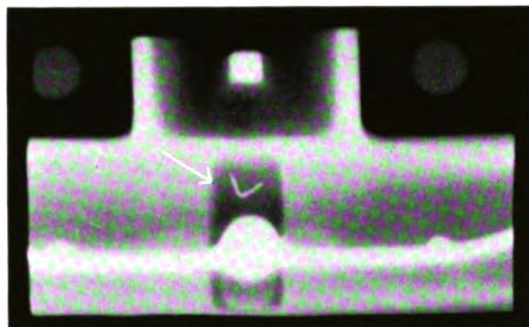


Fig. 119. Inclusion of a Piece of Wire in Magnesium Casting.

(b) *Inclusions of Low Density.*—Particles of impurities consisting of silicates (sand), oxides, sulphides, and sonims which occur mechanically held in the solidifying metal may be collectively called *dross*. The scum of the base metal, consisting generally of its oxides or sulphides, will possess lower density and hence is never as tightly packed as the base metal structure. The radiograph having this defect will reveal gray or dark areas or spots depending on the shape and size of the inclusion.

Oxide inclusions (*dross*), when present, tend to become localized in the cope side of the casting, and will be represented by small dark regions having indistinct outlines. Occasionally, *dross* presents an irregular gray background varying in intensity near the center. This may be further associated with a void due to gas. *Dross* inclusions seldom escape, if at all, detection and adequate identification.

Inclusions of sand from the mold seldom occur, and when these are present, they become localized near the drag side of the casting. Radiographically, sand inclusion has an appearance quite akin to *dross* except that the area of inclusion presents a contrast varying from gray to black with uniform intensity throughout.

Careful manipulation of the founding process will have considerable effect on the diminution of the occurrence. The condition, when present in aluminum alloy sand castings, will be judged for acceptance or rejection by results based on static tests.

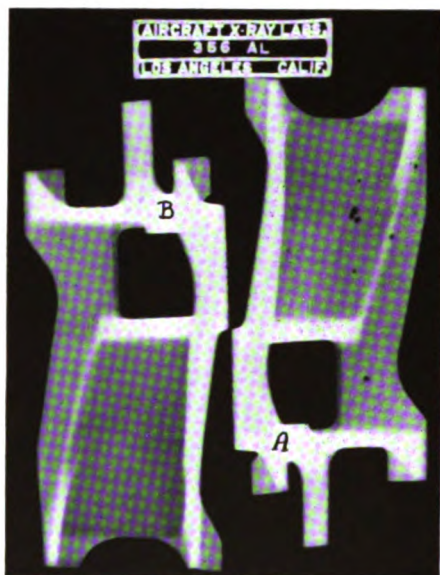


Fig. 120. (a) Dross and Gas-Holes in an Aluminum Silicon Casting. (b) Sound Casting of Same.

(11) MICROSHRINKAGE.—This is a condition due to either intercrystalline shrinkage resulting from improper feeding of the molten metal or due to the presence of fine holes located at the grain boundaries arising from the burning of the eutectic constituents during heat treatment.

The effect appears, in a radiograph, as ill-defined wavy lines, and in magnesium alloy it presents dark feathery streaks or massive areas of relatively definite outlines. The presence of the defect in magnesium alloy castings is undesirable and may cause rejection depending on tests based on static analysis.

(12) SEGREGATION.—The mechanism of segregation is varied and is frequently complex. Some of the numerous causes for segregation are improper compounding of the solute metal in the

alloy solvent; presence of the aggregates of the alloy metals widely separated in their electrolytic dissociation also allied principally to solubility distribution of the alloying elements; per cent composition of the various elements entering into the alloy formation; and, ingot segregation consisting of sulphides and oxides which become insoluble as the metal solidifies, and in tool steel, in addition to these impurities, carbide and phosphorus segregations are very common.

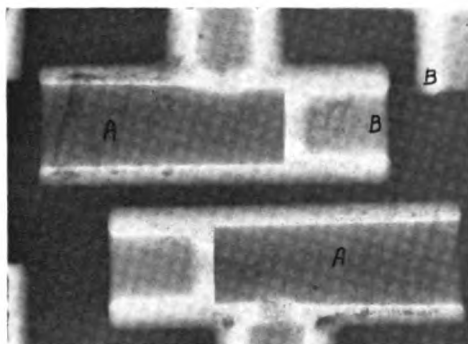
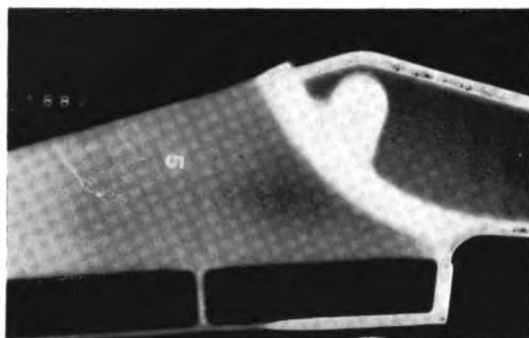


Fig. 121. Magnesium Casting Showing Microshrinkage A, and Excessive Gas Porosity B.

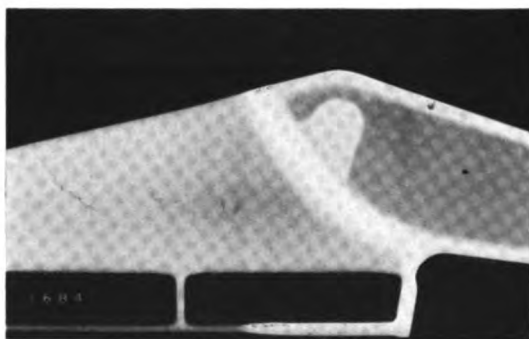
In aluminum-copper alloys, the most prevalent segregation is the copper-aluminum phase, CuAl_2 , which results in consequence to slow solidification of the melt. In magnesium alloys, the tendency for segregation will reside particularly in the occurrence of zinc, aluminum, manganese, and aluminum-zinc-magnesium, though the latter usually occurs as precipitate at the grain boundaries. In beryllium-copper alloys, through a process of high temperature heat treatment, aggregates of elements of lower melting point become more prominent as indicated by the formation of hollow blisters whose interior consists of a mass of burnt metal.

In a radiograph, segregations are generally indicated by well-defined light spots, or white areas of irregular shape, or, by a pattern of long, branched, dendritic or filamentary light areas usually occurring near the gates, during the interim of solidifica-

tion. Fig. 122 illustrates one form of copper-aluminum segregation, which incidentally occurs adjacent the gate.



(a)



(b)

Fig. 122. An Aluminum Alloy Containing Principally Copper and Silicon. (a) A Dendritic Segregation of CuAl_2 . (b) Similar Casting With a Macroshrink at Exactly Same Region.

(13) INTERCRYSTALLINE CORROSION (INTERGRANULAR CORROSION).—It is believed that intercrystalline corrosion is derived by the action of a solution medium which tends to attack the grain boundaries while it produces a protective influence on the crystals. In the case of aluminum-copper alloys, heat treatment at elevated temperatures should be avoided in view of the tendency of the alloy to intercrystalline corrosion. In magnesium alloys, similarly, this corrosion occurs through localized formations of precipitation constituents and their subsequent transfor-

mation into amorphous oxidation phase due to the presence of at least two phases at the grain boundary.

Radiographically, corruptions are identified as irregular, and contrasty dark areas, with outlines delineated at random and consisting of a network of very fine lines. The condition is prevalent near the bosses or near the junction of two sections of widely varying thicknesses. The metal at this portion is very brittle, with considerable attendant reduction in tensile strength. A micrographic specimen made of this section will reveal voids and cracks in the grain boundaries. Castings possessing this imperfection are generally rejectable. Of the various aluminum alloys, aluminum-silicon castings have high corrosion resistance.

(14) MOTTILING.—Mottling, most frequently occurring in aluminum alloy castings, is a condition arising from differences in the chemical composition between the crystals in solution and the precipitation constituents at the boundaries of the grains. In the radiograph, the effect appears as alternate light and dark areas with an indistinct pattern tending to conform to macroscopic grain dimensions. This condition, when occurring in conjunction with a crack, a shrinkage cavity, or with dross, in aluminum sand- or permanent-mold castings, the specimen should be condemned.

(15) SURFACE PITS.—Sharp depressions occurring in the surface of the casting, and frequently ascribed to the voids formed by the escaping gas bubbles from the surface while the metal is still in liquid phase, appear as gas-holes in the radiograph, owing to their dark and rounded or oval shapes. Surface marks, such as produced by Brinell test or Rockwell test, also resemble gas-holes when revealed in the radiograph.

Because of the confusion and uncertainty presented by the above imperfections in a cast part under radiographic examination, it is desirable that every part indicating a defect of the character described above undergo visual examination before arriving at a conclusion regarding the disposition of the material. Decision as to acceptance or rejection due to surface anomalies remains entirely to the materials inspector who refers the part to the x-ray laboratory after his acceptance approval.

(16) EXCESS SURFACE METAL.—As the caption indicates, this is a condition due to fragments of metal adhering to or extending from the surface and are usually formed by the adjoining

crevices or cavities between the various parts of the mold. This may be further due to metals protruding near the gates previous to machining the part. Any excess metal will register, in the radiograph, as a light density area having outlines conforming to the dimensions of the excess metal and to the latter's projection in relation to the x-ray beam. The casting having this condition is acceptable, provided all other factors remain normal.

(17) **INVERSE SEGREGATION.**—During the cooling process of a molten casting, the outer dimensions of the part will solidify first with resultant contraction toward the center. Consequently, an enormous internal pressure will be set up, and which may force the metal in the center still in liquid state out to the surface, forming small globular protrusions. The phenomenon is called inverse segregation or sweating, whose actual mechanism is not fully understood.

In a radiograph, these bead-like bodies will present rounded and light areas with well-defined outlines. The condition, though rare in most light metals, is hardly condemnable in view of its removal during machining.

2. Radiographic Diagnosis of Welds, Forgings, Rolled Metal, etc.—Testing of welds for soundness by x-ray methods dates back to as early as 1918, but the scheme has become officially recognized by the American Society of Mechanical Engineers not until 1931, when, boiler drums and unfired pressure vessels were permitted for the first time to be of welded construction. All such welded seams, however, were required 100% x-ray inspection. The procedure has received such impetus and confidence that fusion welded structures enjoy similar facilities and that production of hydraulic and pressure structures has been speeded up ten fold since the official inauguration of the x-ray examination on welds. The extension of the x-ray testing to constructions of public work projects in the interest of certainty of safety is well recognized by the radiographic testing of all the fusion welding of the penstocks of the power installation at Boulder Dam, amounting to approximately 22 miles of seams requiring 77,000 exposures. Similar radiographic testings are also made on Norris Dam. Within last ten years accomplishments in the welding art have been so great that weld metals have been produced commensurate with the properties of the parent

metal.

It should be pointed out, however, that even with improved technique of welding the possibility of injurious defects such as slag inclusion, cracks, porosity, pipes, and incomplete fusion is everexisting. Hence, several efficient methods have been devised which may be used non-destructively in the determination of the character and extent of these imperfections. Of these, x-ray testing method at present appears to render the most convenient procedure and accurate results. Examination by employing magnetic flux to ferrous materials which are capable

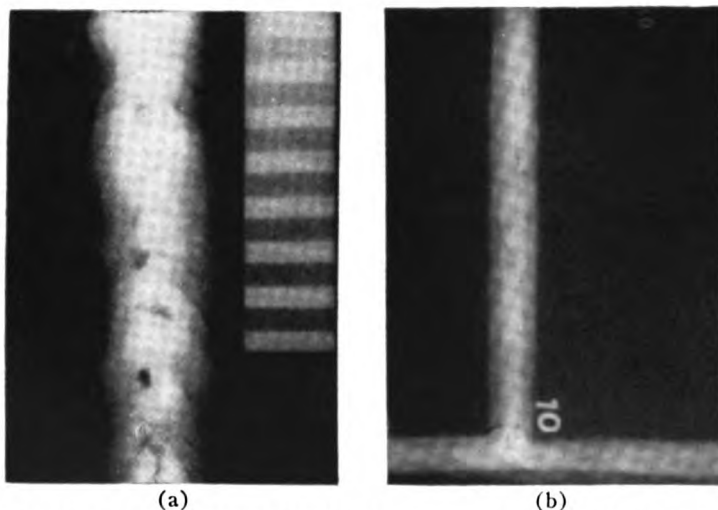


Fig. 123. Radiographs of Welded Specimens Showing (a) Porosity and Shrinkage, and (b) Lack of Fusion and Slag Inclusion.

to become magnetized under the influence of a magnetizing field has found extensive use in detecting fine surface and sub-surface cracks and porosity. The use of this latter inspection, however, is limited to a depth of a few millimeters from the surface, as when the defect is somewhere near the center portion of the metal its detection and subsequent localization is almost impossible owing to the manner of distribution of the magnetic flux. The use of a stetoscope employing sonic principles has been tried to some extent with fairly successful results. Since the scope of this text primarily resides in the treatment of material inspection by x-ray methods, the accompanying discus-

sions will be entirely restricted to the radiographic examination and the interpretation of pertinent findings.

Any imperfection in a weld will curtail a reduction in the thickness and the equivalent density in that region compared with the parent metal. Thus, the defect will be recorded on the radiograph as darkened region corresponding to the size and shape of the anomaly. Similar to sand casting, defects such as inclusion of sulphides, carbides, and oxides, which possess lower densities than the base metal will appear as dark regions of indistinct outlines varying in intensity of contrast. Cracks, pipes, slag, and gas cavities likewise will produce darker filamentary or irregular regions as in the radiograph of a casting having similar defects. These findings should be treated in accordance with the character of the material, its use, and the region to which these defects are confined.

At low kilovoltage ranges, welds thicker than two inches have the tendency to produce scattered radiation which tends to obscure the image. For this reason, continually oscillating Bucky grids are devised which are employed between the specimen and the film during exposures. The insertion of the grid, however, entails an increase in exposure time which could be offset by using high-definition (slow) intensifying screens, or by a slight increase in the voltage applied to the x-ray tube.

At the Aircraft X-Ray Laboratories daily inspection of fusion welds of steel of a thickness up to several inches reveal that the most prevalent discontinuity that occurs in these welds is slag inclusion. Next in order of prevalence are porosity and incomplete fusion, with occasional occurrence of cracks. Many of these radiographic examinations are confined to welded test plates to determine the quality of welding and the technique employed by the welding operator. This procedure curtails a saving in time and labor, as machining of specimens which would not meet the test requirements is eliminated.

Allied to the inspection of welds is that of rolled metals and forgings. This phase of radiography is very limited owing to the excellent methods which are devised and extended to sound forging processes and which eliminate radiographing the part; and, further, due to the safety factor presented by x-ray tested castings, many of the parts that previously were forged are now

cast, thus reducing not only labor and material but also the ultimate production cost. Furthermore, the problem of detecting incipient crack which may be so fine that its visibility to the naked eye is hardly expected is not very encouraging, though such a defect may be picked up by magnetic inspection.

The defects that are commonly detected radiographically in rolled sheets of steel are slag inclusions arising from rolling and forming processes. These generally appear as dark longitudinal fibers running axially to the metal and parallel to the rolling. The effect of poor cold-drawing operation which may be observed frequently in a radiograph of drawn metal readily attests to the worthlessness of the specimen which reveals corrugations of light and dark v-shaped areas tending in the direction of rolling.

The application of radiography to the inspection of ceramics, concrete structures, coal, mica, etc., has proved to be an effective means of determining and discriminating those structures that contain inhomogeneity. The portable field equipment lends itself to the examination of concrete structures, building walls, and their internal contents such as supporting rods, plumbings, electrical wiring, gas conduits, etc., whose location can be readily determined without resorting to destructive methods. Inclusions of metallic particles in molded products, rubber fabrications, various opaque glass items, fiber, textiles, leather, etc., and the determination of the mineral content of coal, cracks in insulators and porcelain sheathings, etc., are readily detectable by a radiographic inspection. The radiographic detection and diagnosis of these imperfections remain identical to those found in metal castings. All discontinuities are represented by dark areas or regions, and inclusions are respectively represented as light or darkened areas, spots, or regions, depending whether the foreign matter has a density greater or smaller than the base material.

In the fruit industry, generally over-all darkened background prevails for sound and normal quality, while crystallization or pithy interior is revealed as specules or as fine light lines running radially from the core of the fruit.

Routine fluoroscopic inspection of canned goods, such as tobacco, boxed candies, etc., carried on conveyor lines can be effectively conducted, as the material composition of these goods

is quite radiotransparent. Therefore, any foreign inclusion such as chips of metal, tack, pin, needle, etc., which may have been inadvertently mixed during the canning or packaging process can be readily detected and sorted out. In the interest of added precaution and of public safety, several large candy manufacturers have been making fluoroscopic examination of all their packaged candies for the past six years.

3. Viewing Radiographs for Diagnosis.—Proper illumination of a radiograph with the view of revealing the minutest interpretable detail structure appears to be of foremost importance to accurate diagnosis. Since the purpose of a radiograph is to furnish evidence regarding the internal constitution of the part that will aid the diagnostician in detecting imperfections and arriving at an accurate and concrete conclusion, it is obvious that proper degree of illumination of adequate quality of color is of utmost significance to the interpretative value of the radiograph. To achieve this purpose, consideration should be directed to the importance of the provision of a subdued general illumination in the diagnosis room, to the proper quality of light furnished by the film illuminator, and finally, and most important, to the ability of the observer to distinguish small differences of density and to his acuteness to perception of detail delineation.

In order that full advantage may be realized from a film illuminator, the criteria to be achieved are the attenuation of the general illumination in the diagnostic room down to 0.7 to 2 lumens per square foot in the region of the film illuminator when its light is turned off, which procedure will eliminate glare, augmenting visual perception; the quality of illumination from the view box approximating north daylight, which character may be obtained from a 14" x 17" fluorescent illuminator using two 15-watt fluorescent lamps, or, using a 250 to 500-watt blue or argon lamp in conjunction with a current-limiting device such as a Variac (a potentiometer); and, an evenly-diffused illumination to bring out even the faintest detail recorded in the radiograph. The brightness of the illuminator surface usually ranges from 1000 to 5000 candles per square foot, the average being approximately 1500 candles per square foot.

It will be evident, then, that the desirability of the selection of a proper illumination (near daylight or bluish-white) to effect

an optimum interpretation value becomes essential not only in the making provision for adequate study of the radiograph but also in the promoting efficiency and comfort in the viewing room. An image having the highest requisite radiographic quality may lose its diagnostic value if viewed by means of a poorly designed illuminator furnishing inadequate illumination. On the other hand, by using a blue-tinted flashed opal glass plate provided with an intensity that will properly illuminate average-density (1.5 H & D density units should be considered as practical in



Fig. 124. Eastman Coldlight X-Ray Illuminator.

industrial work) areas of the radiograph, the diagnostically inferior characteristic of the radiograph may be enhanced materially.

Of the various illuminators of manufacture, those obtainable through Eastman Kodak Company, General Electric X-Ray Corporation, and Buck Exograph Company, appear to present the most popular appeal because of the uniformity and consistency of the illuminations furnished by these lamps. One of these lamps is shown in Fig. 124. The device is furnished with two 15-watt, T-8, Mazda Daylight Fluorescent Lamps, accommodates one 14" x 17" film, and the light from it is of such a mini-

mum temperature that radiographs are not subjected to heat—a serious drawback usually encountered with illuminators of inferior quality and design. This illuminator is 5 inches in depth and is ideal for mounting in the wall, curtailing a saving of space with added convenience.

The provision of spring-clip fingers to afford the securing of



Courtesy Triplet & Barton, Inc.

Fig. 125. A Variable Aperture High-Intensity X-Ray Illuminator.

the dry radiograph against the glass plate, and bracket arms for holding a wet radiograph in its hanger, present additional convenience to the diagnostician who may desire to study the radiograph either after or before it is dry. A further and distinct advantage of the illuminator is accrued in the fact that two or more of the apparatus may fit closely together to form a bank so that more than one radiograph, presumably of the same part

taken from different perspectives, may be viewed at the same time.

A most effective equipment of unique design is the illuminator manufactured by Triplett & Barton, Inc. The device is shown in Fig. 125. Its chief significant features are the provision of a high intensity light source in a concave reflector with variable aperture. When desired, the intensity of the illumination may be varied by means of a potentiometer or a current-regulating device commercially known as a Variac.

4. Determination of Thickness by X-Ray Method.—In industrial radiography, frequently it becomes desirable to determine the thickness of a section of a metal or of a concrete structure of such character that it is almost impossible by ordinary

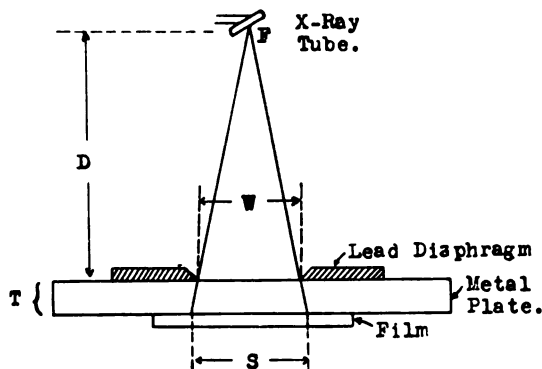


Fig. 126. Thickness Determination of a Metal Plate.

means to measure this except by destructive methods. For instance, the thickness of the wall of a boiler, pressure tank, water mains, or corroded area of a ship's hull, etc., can be accurately determined without recourse to dismantling or physically harming the material. This may be achieved by making a single exposure with the x-ray tube aligned in perpendicular respect to the center of the exposure field. Subsequently, by geometric relations of similar triangles, which are erected by the x-ray beam as the sides and the irradiated surfaces of the object and of the film as forming the bases of the triangles respectively, simple computations are made as illustrated in Fig. 126.

The procedure embodies the positioning of the x-ray tube at

a known distance D from the surface of the metal plate to be inspected. A lead diaphragm is placed in close contact with the plate surface facing the x-ray tube. The plate is then radiographed on a film affixed next to the opposite surface of the plate, as depicted in Fig. 126.

With the x-ray tube properly aligned, the aperture of the lead diaphragm is usually adjusted to a convenient width W , and accurately measured. The shadow S of the metal plate, which is exposed to the x-radiation, can be measured on the finished radiograph. Knowing the target-to-plate distance D , the width W of the diaphragm aperture, and the corresponding width S of the object image, the thickness T of the metal can be accurately calculated by the geometric relations given in equations (95) and (96).

In Fig. 126, the triangle depicted by the vertex F and the base W is similar to the one formed by the same vertex F and the base S . Accordingly, by geometric postulate the bases of two similar triangles are in the same ratio to each other as their respective vertical heights. Hence, we may write the relation

$$\frac{W}{S} = \frac{D}{D + T} \quad (95)$$

and, equating the expression for T , we obtain

$$T = \frac{D \times S}{W} - D \quad (96)$$

where, the thickness T is given in centimeters or inches, in accordance with whether the other quantities are measured respectively in centimeters or inches.

In the event that it is not practicably possible to approximate the film next to the back surface of the metal plate so that a distance R between the film and the plate exists, the expression (96) becomes

$$T = \frac{D \times S}{W} - D - R \quad (97)$$

Equating for the shadow image S of the object, we obtain

$$S = \frac{W (T + D + R)}{D} \quad (98)$$

The application of this method finds wide use in metal industry where accurate knowledge of the size or thickness of the parts that are exposed to constant wear and tear is desirable in order that replacements, where necessary, can be effected.

5. X-Ray Method of Calculating Depth of Defect.—Occasionally it becomes desirable to determine the depth of a defect, such as of a gas hole, crack, inclusion, or shrink, detected especially in heavy parts or welds. This is of advantage in order to precisely tell whether or not the stress requirements of the part examined are seriously curtailed due to the position of the flaw. In the case of heavy welds, should a defective condition be found to exist, the procedure permits the detection of the defect and its location from the surface so that excessive chipping and repair welding are reduced to a minimum, thus making it lucrative from time and economy viewpoints. Either a fluoroscopic or a radiographic method may be employed in this determination.

If the localization of the depth of the defect is to be performed by use of a film, the procedure is conducted by making two exposures from two different angles preferably on the same film. To accomplish this, measurements are taken of the target-to-film distance, the distance through which the x-ray tube is to be moved, and the distance of the corresponding displacement of the image of the defect. Finally, by equating the ratios of the corresponding dimensions of the two similar triangles depicted between the target and the film, the depth of the defect from the given surface is accurately calculated.

In Fig. 127, a beam of x-rays projecting from the source S (the target) passes through the defect B in the specimen P and forms the image of B at M . The x-ray tube is then shifted to the position represented by S' , an equal distance from C , and another exposure is made with the image indicated at M' . If the two exposures are made on the same film, the normal exposure time should be halved for each exposure, whereas for two separate films the normal exposure should be in effect for each. The depth d of the defect from the surface of the film may be determined by the following expression evolved from known geometric relations depicted in Fig. 127.

$$d = \frac{MM' \times D}{MM' + SS'} \quad (99)$$

where, MM' is the displacement of the image, D is the target-film distance, and SS' is the total displacement of the x-ray tube. The values of the quantities may be given either in centimeters or in inches.

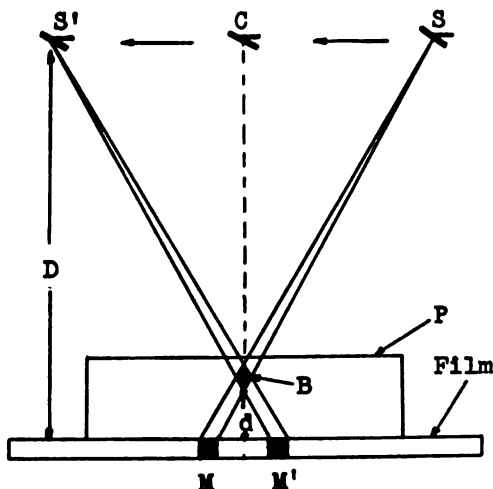


Fig. 127. Measurement of the Depth of a Defect in a Part.

6. Practical Examples on the Determination of Thickness and Depth of a Defect.—(a) *Thickness determination.*—For determining the thickness of a certain hydraulic pressure tank, the x-ray tube is positioned 24 inches from the outside surface of the tank. Against this surface is placed a lead diaphragm with its aperture adjusted to 6 inches. With the film affixed in close contact with its inner surface, the tank is radiographed. An image magnification of 1.2 inches is obtained when the film is processed. (1) Find the thickness of the tank at this region. (2) If the film were placed $\frac{1}{2}$ inch from the inner surface of the tank (due to possible protrusions of the heads of the bolts or rivets at the seams) what would be the enlargement of the image at this distance from the x-ray tube?

(1) From equation (96), the thickness of the tank at the region specified in the problem will be

$$T = \frac{D \times S}{W} - D \quad \text{where,} \quad \begin{array}{l} D = 24 \text{ inches} \\ S = 7.2 \text{ inches} \\ W = 6 \text{ inches} \end{array}$$

Substituting the numerical values of the quantities, we obtain

$$\begin{aligned} T &= \frac{24 \times 7.2}{6} - 24 \\ &= \frac{172.8}{6} - 24 \\ &= 28.8 - 24 = 4.8 \text{ inches. } \textit{Ans.} \end{aligned}$$

(2) To find the magnification of the image at the above given second distance, we write the equation (98) and solve for the size of the image S . Thus

$$S = \frac{W(T + D + R)}{D}$$

where, R is numerically equal to $1/2$ inch. Therefore, by substituting the numerical values, we obtain

$$\begin{aligned} S &= \frac{6(4.8 + 24 + 1/2)}{24} \\ &= \frac{28.8 + 144 + 3}{24} \\ &= \frac{175.8}{24} = 7.325 \text{ inches (image size)} \end{aligned}$$

The magnification will then be $7.325 - 6 = 1.325$ inches. *Ans.*

(b) *Determination of Depth of a Defect.*—An aluminum casting, 4.25 inches in thickness, is found, by a radiographic evidence, to have a gas hole in its interior. Owing to the character of function of the specimen, it has been decided that the accurate size and the depth of the void from the surface be determined in order to arrive at a conclusion regarding its disposition. Furthermore, densitometric measurements of the radiograph have indicated that the area covered by the image of the defect has a density of 1.25 (based on H & D unit) and that of the contiguous base metal is found to be as 1.20. With a target-film distance of 36 inches, when the x-ray tube is shifted 4.2 inches to either side from the central position, the image of

the gas hole moves through a distance of 0.8 inch. Find (1) the depth of the defect from the surface of the casting, and (2) determine the vertical dimension of the void.

(1) In accordance with equation (99), the depth of the defect from the film may be computed as

$$d = \frac{MM' \times D}{MM' + SS'} \quad \text{where, } \begin{array}{l} MM' = 0.8 \text{ inch} \\ SS' = 8.4 \text{ inches} \\ D = 36 \text{ inches} \end{array}$$

$$d = \frac{0.8 \times 36}{0.8 + 8.4}$$

$$= 3.13 \text{ inches.}$$

The gas, then, is located 3.13 inches from that surface of the casting which is next to the film. In the problem, it is desired to determine the depth of the void from the upper surface of the specimen. Since the vertical thickness of the casting was given as 4.2 inches, the defect is, therefore, located at a distance $4.2 - 3.13 = 1.07$ inches below the upper surface of the part. (Note: In referring to the distance of the defect from the surface the inference resides in the linear distance between the center of the defect and the surface of the casting.)

(2) Assuming that the density-thickness relation curve at the range given is linear (and the assumption in effect is justifiable for the case in hand), we may calculate the vertical dimension by first computing the thickness of the part at the section reduced due to the presence of the gas hole as

$$\frac{1.20 \times 4.2}{1.25} = 4.03 \text{ inches.}$$

The vertical dimension of the void, then, will be determined by the difference of the two thicknesses of the specimen. Hence, we have

$$4.2 - 4.03 = 0.17 \text{ inch. } \textit{Ans.}$$

CHAPTER IX

METALLURGICAL CONSIDERATIONS

1. Physical and Mechanical Properties of Materials.—The inherent characteristics which distinguish one substance from the other are referred to as *physical properties*. In the periodic chart of the chemical elements, it will be noted that the elements are arranged following the order of their increasing atomic weights, and each element is assigned with an atomic number corresponding to the number of planetary electrons (extranuclear electrons) which determine the chemical properties of that element. It is further noted that elements with similar properties in general are listed in separate columns. For instance, the element lithium, sodium, potassium, rubidium, and cesium are presented as one group in the first vertical column, and are known as strong alkali metals; calcium, barium, and strontium are grouped in another column and are called alkali earth metals; iron, cobalt, and nickel constitute a sub-group referred to as ferrous group; and, a number of other groups which exhibit similar elemental qualities based on their physical and chemical behaviors are similarly grouped together.

In describing the physical behavior of a substance such characteristics as color, density, specific heat, specific resistance, melting point, electrical conductivity, coefficient of thermal expansion, etc., may be included. Those physical properties which involve the industrial applications and fabrication processes of substances under mechanical usage are referred to as *mechanical properties*. These latter properties are characterized by elasticity, ductility, stress, strain, hardness, machinability, strength, etc. From the view point of the engineer, the mechanical properties of materials are of special significance because of their providing an empirical information in the selection of materials for use for the specific purpose in hand.

The characteristics of different materials are determined on the basis of the behavior of each material under test by precision laboratory methods under specific and controlled conditions. That is, in the determination of the mechanical property of a substance,

factors such as, for instance, ductility of the metal, the atmospheric pressure, and the room temperature together with other variables under which the test is conducted should be taken into consideration. Since ductility varies directly with temperature, it will be evident that a metal at high temperature (below fusion point) will be more ductile than when it is cold or at room temperature. A metal under continued elastic deformation at high temperature will undergo a permanent plastic deformation, whereas at room temperature a continued plastic deformation below elastic limit may remain an elastic deformation; that is, when the load causing the deformation at low temperature is removed, the metal regains its original form. The testing methods by which the physical characteristics of a substance are determined are known as *physical properties*, while those by which mechanical behaviors are determined are termed *mechanical properties*.

2. Elasticity and Plasticity.—In the normal state of a substance, all the atoms composing it are held at definite space relationships and are in a state of equilibrium by the interaction of the atomic forces. When these forces are disturbed as by the application of an external force on the substance, a temporary (elastic) deformation due to the displacement of the atoms in the space lattices will be experienced in approximate proportion to the applied force. Atoms thus displaced temporarily and tending to regain their original positions are in a state of strain. Removal of the acting force, and hence the stress, results in the gradual recovery of the substance with simultaneous extinction of the strain. This property which affords the substance to recover from a deformation upon removal of the external force is known as *elasticity*.

All substances possess elasticity to some extent, although this property may be very limited in certain types of materials such as stone, marble, ores, or iron. The range of elasticity in different materials is one of degree also dependent on the completeness of recovery. Comparing spring steel with rubber, the latter will undergo relatively a greater magnitude of elastic deformation than steel when subjected to identical external forces. But, the recovery of the former will be more complete than rubber, and, therefore, steel is considered to be more elastic from the

standpoint of the construction engineer.

The elongation produced on a substance within elastic limit may be expressed quantitatively by Young's modulus (modulus of elasticity), which may be given as

$$E = \frac{FLg}{Ac} \quad (100)$$

in which, E is the modulus of elasticity given in pounds per square inch, F is the applied force in pounds, g is the acceleration due to gravity equal to 32.17 feet per second per second at sea level, L is the original length in inches and A the cross-sectional area in square inches of the substance, and e is the elongation produced by the applied tension.

On the other hand, if the stress on the material is carried far beyond its *elastic limit*, permanent deformation will result. Under such a condition the displacement of the atoms in the metal is of such character that they are unable to regain their original positions. A metal or a substance in such a state is said to have undergone a plastic deformation, and the property of the metal by virtue of which this change occurs is known as *plasticity*. The plastic deformation behavior of substances then applies to a condition opposite to elastic deformation.

Many of our industrial fabrications and metallurgical operations involve the application of the plastic behavior of metals. Evidences of these processes are brought to light in the die-stamping of various automotive parts and electrical fixtures, forgings of aircraft materials such as propellers, shafts, frame structures, etc., drawing of electric wires and cables, extrusion of pipes, tubings, and important hydraulic products; spinning of aluminum, annealed stainless steel, and copper; and, rolling of sheet metals, springs, etc. The principles of plastic deformation have become to occupy such an important place in industry that many metal fabrications, and structures of manufacture, which previously involved the use of time-consuming welding processes, are now produced by die-stamping, forging, and by extrusion. The process has, indeed, curtailed a saving of millions of dollars annually to metal manufacturing industry, aside from the superior quality of endurance and appearance afforded

by products of manufacture through operations involving plastic deformation.

It should now be obvious then that a material which possesses a high degree of elasticity such as chrome-molybdenum steel will make good springs, while that such as gold, aluminum, or copper, possessing a high degree of plasticity will have good cold-forming properties.

3. Stress and Strain.—A distribution of forces internal to the metal and acting between the atoms to resist deformation is called *stress*. In order to create this stress the atoms must be influenced by an external force, and expressed quantitatively, the force applied per unit area of the surface will be the stress. If a weight of, for instance, 40 pounds acts, in a tensile manner, on some material having a cross sectional area of 5 square inches, and at right angles to the line of force the stress will be given as 8 pounds per square inch. Expressed in an equation form, we have

$$S = \frac{F}{A} \quad (101)$$

in which, S is the stress given in pounds per square inch, F is the applied force in pounds, and A is the cross-sectional area at right angles to the line of force and is given in square inches.

Within elastic range, gradual deformation of a metal under a steady load is directly proportional to the magnitude of the stress and to the temperature at which the load is acting. When sufficient time is allowed, the condition will result in plastic deformation. Such a process in which plastic deformation occurs at a low rate is called *creep*.

In industry, various high-pressure structures operating under high temperatures have great tendency to yield to creep formation, and hence at present the condition has become an important yet not unremediable problem to the construction and designing engineer. Static tests are performed on structures of prime importance prior to the assembly in an effort to improve and eliminate the causes that will materially enhance the service life of the material due to slow deformation by constant internal stresses.

A study of creep rate diagrams indicate that the process is a direct function of time, and the rate of deformation is sur-

prisingly variable and is dependent on the physical conditions influencing the distribution of forces internal to the metal. While the problem of complete elimination of creep has not been fundamentally solved by any means, it remains to some future research to further lighten the subject of controlling the stress distribution and re-enforcement of slip planes and their goniometric orientation possibly through more advanced methods of recrystallization mechanism in metallic bodies.

The establishment of lattice plane distortion in the crystalline structure of the metal resulting from stresses set up by the application of an external force qualitatively may be called *strain*. Strain, then, is the resultant deformation produced by sustained internal stress. A material under strain usually is in the process of undergoing deformation. Gross defect is one of the determining factors in the failure of many metal structures and which may readily be detected by a radiographic examination. But, many metal products which have been resolved radiographically as perfectly sound have failed in service. Concern may be directed to the cause as residing in a number of physical states of which internal strain occupies one of the foremost domains, which condition cannot be directly determined by mere radiographic indications. Recourse may then be had to the qualitative analysis of such an anomaly by photomicrographic procedure, or to the quantitative estimation by x-ray diffraction patterns.

As has been referred to above, strain is a deformation arising from the application of an external force which has acted in a direction normal to the plane of the cross-sectional area of the material under consideration. The length of a body under strain, then, will increase by some fraction per given unit length, and this ratio is quantitatively expressed as

$$s = \frac{e}{L} \quad (102)$$

where, s stands for strain in inches per inch, e is the total change in length in inches, and L is the length of the material and is given in inches.

For example, let us assume that a certain aluminum bar of a length of 12 inches has stretched 0.001 inch under a given load.

The strain can be calculated by dividing the total increase in length, 0.001 inch, by the original length or 12 inches, which gives $0.001/12 = 0.000083$ inch per inch.

The maximum stress which a material may undergo without permanent deformation is known as *elastic limit* of that material, which in the sense herein given is the proportional elastic limit, which is further pertinent to tensile strength. It should be clearly kept in mind that *a material of high degree of elongation has a low tensile strength, and one having low degree of elongation possesses a high tensile strength*. In metallurgical operations this fact is taken into serious account from the viewpoint of designing structures of high stress service conditions for endurance and safety in operation.

Exceeding the elastic limit of a material by the continued increase in the applied load a stress condition is obtained whereby the material continues to elongate without further increase in load. The stress at which this condition occurs is called the *yield point*, which has direct bearing on the ultimate tensile strength of the body.

Metal parts subjected to alternating stresses such as by the engagement and disengagement of automotive gears, tortional stresses on the shafts by the pull of the belt, impact stresses, and vibrations causing repeated application of stress, may produce mechanical failure which is called *fatigue*.

In producing fatigue, the part under consideration is subjected to repeated tension and compression, causing small plastic deformations at each maximum tension and compression process. But, the deformation produced by the tension is opposite in direction to that produced by compression that the resultant apparent deformation is null. This, however, does not take into account the behavior of the internal structure, which gives rise to *work hardening*.

Work hardening, indeed, appears to be the nucleus of a number of causes giving rise to changes in the interstices of the metallic crystals precedent to failure. That is, when work hardening is carried to such an extreme degree that no further plastic deformation in unison with the direction of movement can take place due to extreme fatigue condition of the metal, small incipient cracks are formed usually at the point of greatest stress.

These cracks eventually may extend to the surface, diminishing the cross-sectional dimension of the base metal, and causing a sudden failure. Many materials of industry, at present, possess a high degree of mechanical quality (due to new methods of control, and processing materials of manufacture), and failure may occur only after a long and continual operation at the maximum stress. The quality of the material to withstand maximum number of cycles of stress without failure, is known as *endurance limit*. Above this limit, the formation of incipient cracks acting as localized concentrations of stress gives rise to a progressive fracture frequently extending to the surface of the metal.

4. Ductility and Hardness.—The quality of a material which will undergo a plastic elongation under sustained stress is known as *ductility*. The elongation extended beyond the yield point of the material until the failure of the specimen occurs is a qualitative measure of its degree of ductility. This may be determined by taking a specimen of known length and of known cross-sectional area (usually the portion of the specimen under test, measuring 2 or 8 inches long and respectively 0.505 and 0.857 inch in diameter) and subjecting it to maximum elongation until the specimen fails. The broken ends are placed together and the elongation is measured. By multiplying the total change in length by 100 and dividing the product by the original length (gage length) of the specimen will give the per cent elongation of the specimen.

As an illustration, assuming that a certain nickel bar 8 feet long with a diameter of 0.5 inch supports a dead weight of 800 pounds, what will be the per cent elongation of the specimen at sea level?

Using the stress-strain equation (100), the total change in length of the steel bar will be

$$e = \frac{FLg}{AE} \quad \text{where,} \quad \begin{aligned} F &= 800 \text{ pounds} \\ L &= 8 \times 12 = 96 \text{ inches} \\ A &= 0.196 \text{ square inch} \\ E &= 29 \times 10^6 \text{ lbs./sq. in.} \\ g &= 32.17 \text{ ft./sec.}^2 \end{aligned}$$

$$e = \frac{800 \times 96 \times 32.17}{0.196 \times 29 \times 10^6}$$

$$= \frac{24706.56}{5.684 \times 10^6} = 0.43468 \text{ inch.}$$

According to our statement that the per cent elongation will be equal to the product of the total change in length of the specimen multiplied by 100 and divided by the original length, we may equate

$$\begin{aligned} \text{Per Cent Elongation} &= \frac{0.43468 \times 100}{96} \\ &= 0.452 \% \quad (\text{approx.}) \quad \text{Ans.} \end{aligned}$$

The property of a substance to resist penetration by another body is called *hardness*. This definition may further be extended by stating that hardness is the ability of a substance to offer resistance to scratch or wear. The term hardness has quite general aspects as used here, as it is dependent on the form of stress to which the material under consideration is subjected in exhibiting various manifestations of hardness. For instance, by scleroscopic test, it will be observed that hard rubber indicates relatively identical hardness as mild steel, but when tested by Brinell process it is impossible to take any readings due to excessive deformation. Diamond is harder than lead, whereas the latter can scratch a diamond crystal when rubbed at a plane normal to the lattice surface. It is evident then that the hardness quality of a substance is rather indefinite and the manifestations of tests are resultant of complex combinations of physical characteristics.

In the determination of the properties of a metal especially that which is subjected to heat treatment or hardening process, a reasonably accurate account of the hardness of the material is of decided importance in considerations regarding the acceptance and rejection of the product. Although such a test requires a discreet knowledge of the behavior of the different metals in their response to various test processes, nevertheless a skillful operator can readily adapt his technique to meet the situation in hand in the accounting for the significance of the test.

It should be kept well in mind, however, that to think of hardness as a basis for applying its quantitative value to every case in the estimation of the tensile strength would be fallacious. Many hard substances, such as glass, bakelite, and certain cast

white metals, possess low tensile strength. On the other hand, certain soft metals resist abrasion whereas harder metals under identical physical conditions may fail the test. Some of the tests that are commonly used in determining hardness are Brinell, Vickers, Rockwell, and scleroscopic methods.

(a) *Brinell Hardness Test*.—The determination of Brinell hardness of a metal may be achieved by impressing a hardened



Fig. 128. The Universal Production Brinell Tester.

steel ball, usually 10 millimeters in diameter, against the plane finished surface of the metal to be tested, and taking measurements of the impression made under a definite static load. The test has decided advantages, provided that it is conducted under conditions whereby the hardness of the surface does not approach that of the ball. In the latter case, concordant results may be expected and that close relationship between hardness and maximum tensile strength may be established within reasonable accuracy.

To perform the test, the material, such as steel or iron, is placed on the press table of the Brinell machine, shown in Fig. 128, and a load of 3000 kilograms using a steel ball of 10-millimeter diameter is impressed on the specimen, and the pressure is maintained for 30 seconds and then released. For soft metals, a 10-mm ball with a pressure of 500 kilograms is used. Beyond a Brinell value of 500, a 10-mm tungsten carbide ball or a spherical diamond penetrator is employed.

So that the Brinell hardness number of a metal will remain reasonably constant, the applied load should be proportional to the square of the ball diameter with time of impressure remaining constant (30 seconds). For instance, for a given hard metal, such as steel, iron, beryllium-copper, or materials of similar hardness, a load of 3000 kilograms with 10-mm ball or 750 kilograms with 5-mm ball may be used to obtain the same Brinell value. That is, 3000 is to $(10)^2$ as 750 is to $(5)^2$, or $3000 : 100 :: 750 : 25$, the ratio in either case remaining 30 : 1, or $P = 30D^2$, where P is the applied load in kilograms and D is the diameter of the ball in millimeters. For soft metals, such as aluminum, magnesium, copper, zinc, bronze, etc., this ratio is taken as 20 : 1, or $P = 5D^2$. Moreover, the size of the test ball must be so selected that the resultant ball impression on the surface of the specimen will remain within the range of 25% to 50% of the diameter of the sphere.

In calculating the Brinell hardness number, at least two measurements of the diameter of the ball impression are taken usually at right angles to each other, and formulated in conjunction with known values of the impressed load and the ball diameter. This value may be obtained by dividing the applied load in kilograms by the area of the spherical impression formed on the surface of the test specimen. Thus, we have

$$H_B = \frac{P}{A} \quad (103)$$

where, P is the impressed load in kilograms, A is the area in square millimeters of the spherical impression, and H_B is the Brinell hardness number.

Since the area of the spherical impression is a geometric relation, we shall make recourse to Fig. 129, in which D stands for

the diameter of the ball, and d is the greatest diameter of the spherical impression. The surface area A_c included between the

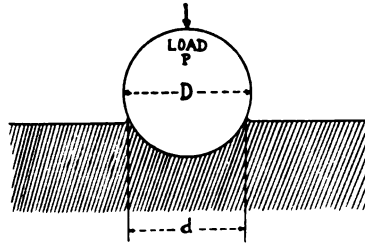


Fig. 129. Illustrating the Formation of an Impression on the Test Specimen by Brinell Indenter.

plane of the circle of diameter D and that of the circle of diameter d is given as

$$A_c = \frac{\pi D}{2} \sqrt{D^2 - d^2}. \quad (104)$$

Furthermore, the area of one-half of the sphere of diameter D is equal to $\pi D^2/2$. Therefore, the area A_s of the spherical impression made by the ball is the difference of the two areas; that is,

$$A_s = \frac{\pi D^2}{2} - \frac{\pi D}{2} \sqrt{D^2 - d^2}. \quad (105)$$

Hence, expressing the Brinell value quantitatively, we obtain

$$HB = \frac{P}{\frac{\pi D^2}{2} - \frac{\pi D}{2} \sqrt{D^2 - d^2}} \quad (106)$$

where, P is the impressed load in kilograms, D is the diameter of the penetrator in millimeters, and d is the diameter in millimeters of the ball impression.

Provided that the penetrator balls are not deformed during the process of loading and that the impression made by the ball is

perfectly spherical, the above formula will be applicable in general. In order to eliminate computations, Brinell hardness numbers for 3000 kilograms (or for 500 kilograms) with 10-mm ball, and for 750 kilograms with 5-mm ball are given with their equivalent Rockwell numbers in convenient table forms.

Example:—An aluminum-silicon-magnesium casting has been Brinell tested with a 500-kg load and 10-mm steel ball. The diameter of the ball impression is measured as 4.36 millimeters. Find the Brinell number of the metal.

According to equation (106), we have

$$H_B = \frac{P}{\frac{\pi D^2}{2} - \frac{\pi D}{2} \sqrt{D^2 - d^2}}$$

$$\begin{aligned} \text{where, } P &= 500 \text{ kilograms} \\ D &= 10 \text{ millimeters} \\ d &= 4.36 \text{ millimeters} \end{aligned}$$

$$\begin{aligned} H_B &= \frac{500}{\frac{3.1416 \times (10)^2}{2} - \frac{3.1416 \times 10}{2} \sqrt{(10)^2 - (4.36)^2}} \\ &= \frac{500}{\frac{314.16}{2} - \frac{31.416}{2} \sqrt{100 - 19}} \\ &= \frac{500}{157.08 - 15.708 \times 9} \\ &= \frac{500}{15.708} = 31.9 \text{ (approx.) } \text{Ans.} \end{aligned}$$

(b) *Vickers Hardness Test.*—Vickers hardness test is based on the same principles involving the use of the Brinell tester, the principal difference residing in the shapes and sizes of the indenters and in the magnitudes of the applied loads. Compared with Brinell hardness values on steel the numbers remain practically identical up to a hardness of 300, but beyond this number the Brinell values fall progressively, and above 600 the Vickers hardness is a more reliable measure, since the penetrator is not subject to deformation.

The Vickers indenter is a square-based diamond pyramid ac-

curately cut and polished to precision so that the impression made is independent of depth. The angle subtending any two opposite faces is 136° , so chosen as to give concordant numbers as of Brinell scale. The applied load varies from 1 to 120 kilograms in accordance with the dimensions of the test specimen. The whole operation is almost entirely automatic. A cam mechanism controls the application of the load and the time interval which may be standardized at 10 seconds (30 seconds being the prevalent interval). The impression is read by means of a permanently mounted microscope which swings into position automatically and affords a sensitivity of 0.00005 inch.

In practice, the measurement of the indentation which appears as a dark square against a light ground is performed by determining the dimension of any one diagonal across the square in millimeters, and the hardness number corresponding to the diagonal length is read directly from pertinent charts. However, if charts are not available, computations of the hardness value may be made in accordance with the expression

$$H_v = 1.854 \frac{P}{D^2} \quad (107)$$

in which, H_v is the Vickers hardness in kilograms per square millimeter, P is the applied load in kilograms, and D is the length of the diagonal of the impression and is given in millimeters.

The derivation of equation (107) may be executed by a fundamental consideration of the principle step by step. As in Brinell hardness, the Vickers number is equal to the applied force divided by the area (of the pyramidal impression). Hence, we have

$$H_v = \frac{P}{A} \quad (108)$$

where, P is the impressed load in kilograms, and A is the lateral area of the pyramidal impression.

The surface area of the pyramidal impression made by the penetrator shown in Fig. 130 is given as the product of the perimeter $4S$ and one-half the slant height h . That is

$$A = \frac{4Sh}{2} \quad (109)$$

where, A is the area in square millimeters of the pyramid, S is

the lateral dimension in millimeters, and h is the slent height in millimeters.

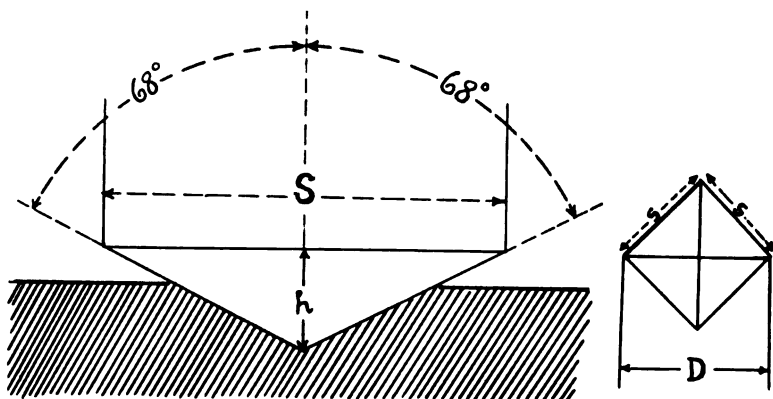


Fig. 130. Schematic Diagram of Vickers Diamond Indenter and the Area of the Impression Made on the Test Specimen.

From geometric relations, the side S is equal to $D/\sqrt{2}$. Thus, substituting $D/\sqrt{2}$ for S in equation (109) we obtain

$$A = \frac{4Dh}{2\sqrt{2}} = \frac{2Dh}{\sqrt{2}} \quad (110)$$

The quantitative relation of the slent height expressed trigonometrically will be equal to one-half the slent height divided by the sine of angle 68° (which is one-half of 136° , the standard angle between opposite surfaces of the pyramid). Thus,

$$h = \frac{S}{2 \sin 68^\circ} = \frac{D/\sqrt{2}}{2 \sin 68^\circ} \quad (111)$$

Substituting the value of h from equation (111) in equation (110) and simplifying, we obtain

$$A = \frac{2D}{\sqrt{2}} \times \frac{D/\sqrt{2}}{2 \sin 68^\circ}$$

or,

$$A = \frac{D^2}{2 \sin 68^\circ} \quad (112)$$

where, D is the diagonal length in millimeters of the square indentation made by the pyramidal penetrator, and 68° is the angle between the lateral surfaces of the pyramid and the vertical passing through the center of the plane of the square.

The success of the operation of the machine is primarily dependent on the manner of care received by the apparatus rather than on the skill of the operator. A further factor requisite to the realization of accurate results is the requirement of high magnitude of smoothness of the surface under test. All traces of even small scratches should be removed completely before an attempt is made to perform the indenting operation.

(c) *Rockwell Hardness Test*.—This method of hardness testing consists of measuring differentially the depth of penetration by a steel ball, or a diamond cone, under specific conditions of load. There are two common standard hardness scales corresponding to two types of penetrators. One of these is a hardened steel ball of a diameter $1/16$ inch and is designed as B scale indenter, and the other is the diamond cone (Brale) with 120-degree angle, and is designated as C scale penetrator. One other type, which is less commonly employed, is the E scale penetrator and consists of a steel ball of $1/8$ inch in diameter. The Rockwell hardness testing machine is shown in Fig. 131.

The principle of operation of the test involves the application of a minor load of 10 kilograms to the penetrator adjusted on the surface of the test specimen, and the indicator is set to zero, or at the point marked "Set." This done, the major load consisting of 60 to 100 kilograms for soft metals, and 150 kilograms for hard metals is applied for 5 or 4 seconds respectively depending on the hardness of the material. When the major load ($100 - 10 = 90$ kilograms, or, $150 - 10 = 140$ kilograms) is removed, with the minor load still sustained, the increase in impression of the penetrator is measured directly in Rockwell hardness number on the indicator dial. The scale of the latter dial is reversed so that a deep impression gives a low reading and hence indicating a soft material, whereas a high reading due to shallow penetration is an indication of higher degree of hardness.

Achievement of a high degree of accuracy is ensured when surfaces to be tested are made fairly smooth, and, where necessary, the scale or the oxidized skin, is removed precedent to the

test in order that the true representative hardness of the metal may be obtained. The thickness of the specimen under investigation should be such that the penetration does not leave any indentation mark on the opposite surface of the specimen after



Courtesy Wilson Mechanical Instrument Co., Inc.

Fig. 131. The "Rockwell" Hardness Tester.

the test operation. True hardness readings of hard steels as thin as 0.027 inch are possible, but with softer metals such as aluminum, magnesium, or zinc, greater thickness of the specimen becomes necessary.

Brinell equivalents of Rockwell hardness numbers on the two standard scales, B and C, may be obtained within an accuracy of 10 per cent by means of the following equations taken from the U. S. Bureau of Standards' Research Paper No. 185:

$$H_B = \frac{7300}{130 - R_B} \quad (113)$$

where, H_B is the Brinell hardness number, and R_B is the Rockwell number taken on B scale for values between 40 to 100, and using a 1/16-inch diameter ball with 100 kilograms.

$$H_B = \frac{1,520,000 - 4,500 R_C}{(100 - R_C)^2} \quad (114)$$

in which R_C is the Rockwell hardness number taken on C scale for values between 10 and 40 at an impressed major load of 150 kilograms.

$$H_B = \frac{25,000 - 10(57 - R_C)^2}{100 - R_C} \quad (115)$$

where, R_C is the Rockwell number taken on C scale for values between 40 and 70 at an impressed major load of 150 kilograms.

When the Rockwell number of a steel specimen is known, the tensile strength (lbs./in.²) may be calculated within an accuracy of 85 per cent by use of the following equations:

$$\text{Tensile Strength} = \frac{1,750,000 - 12,000 R_B}{130 - R_B} \quad (116)$$

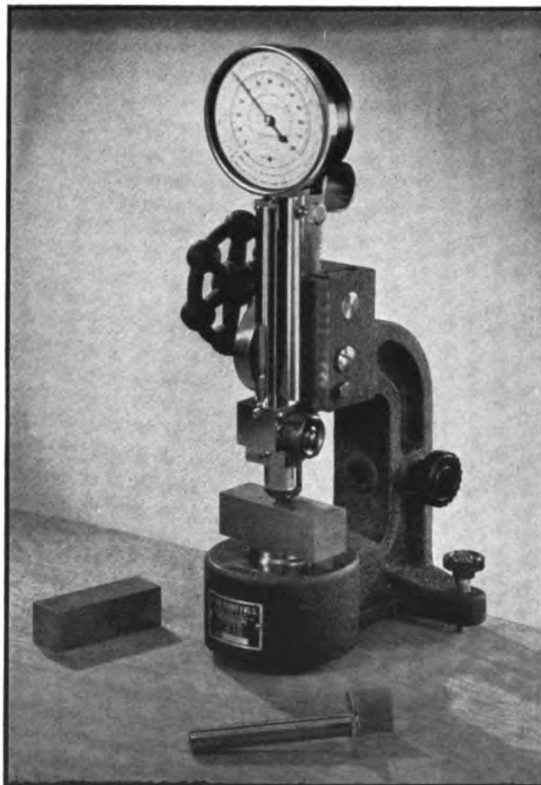
$$\text{Tensile Strength} = \frac{10^5(7,000 - 10R_C)}{(100 - R_C)^2} \quad (117)$$

in which equations, the respective impressed load values and the diameters of the indenting balls used respectively with R_B and R_C scales are conserved.

Where only a shallow impression is permissible, such as in the case of thin sheets of metal, diaphragms, razor blades, or carburized steel materials which can not be directly tested by any of the above given methods, the Rockwell superficial testing scheme is particularly useful. It operates on the same principle as the regular Rockwell machine, and uses either a 1/16-inch steel ball or the N-Brale penetrator, which penetrates to a fraction of the depth of the normal "Rockwell" Tester. Only differences that reside are in the applied minor loads, and in the comparatively greater sensitivity of the depth measuring system. The

minor load consists of 3 kilograms, and the major load ranges 15, 30 and 45 kilograms.

(d) *Scleroscopic Hardness Test.*—The scleroscopic hardness tester measures the elastic hardness or resilience of the material by indicating the rebound of a diamond tipped hammer from



Courtesy Shore Instrument Mfg. Co.

Fig. 132. The Shore Scleroscopic Hardness Tester.

the polished surface of the test object. The height of the rebound is selected on the basis of an arbitrary scale of 100 to which the hammer will rebound from the surface of hardened tool steel. Such a scheme permits the testing of very hard and brittle material for which Rockwell or Brinell method is not applicable. Since the rebound of the diamond hammer is dependent on the difference of energy between the striking energy and that

absorbed by the surface of the test specimen, naturally softer materials such as lead, aluminum, or zinc will not give as great a reading as harder materials.

The device is shown in Fig. 132, and consists of a glass tube with hardness scale inscribed within it. Through this tubing the diamond hammer is guided during its fall controlled by a suction rubber air bulb. The hammer essentially is a cylindrical metal plug and weighs about 40 grams. At the tip of this hammer is mounted the diamond indenter, which upon striking the surface of the test specimen produces a momentary pressure of about 450 tons per square inch. The success of the test primarily resides in the suitable clamping of the specimen so that any vibration or movement due to impact is eliminated. The condition further resides in the accuracy of aligning the hammer in a position perfectly normal to the test surface.

(e) *The Standard Tension Test.*—The tension test indicates the hardness of a material in terms of its elastic limit and its ultimate tensile strength. For most satisfactory specimen dimensions for ordinary testing, the standard round specimen shown in Fig. 133a or flat specimen shown in Fig. 133b are chosen. In such specimens the gage length is equal to 4 times the diameter of the reduced section of the specimen. The standard diameter for a two-inch gage-length specimen shown in Fig. 133 (a) or (b) is 0.505 inch, and that for one-inch gage length is 0.252 inch. When it is desired to use smaller specimens, a geometrically similar specimen should be employed; that is, the ratio of the gage length to the diameter should preferably remain 4 to 1. However, other dimensional ratios are also in effect in practice, and these should be determined from pertinent specifications.

The extremities of the test specimen are usually enlarged so as to permit the proper mounting in the test machine. These ends may be either threaded or plain to suit the particular testing apparatus. When threaded, the pitch should not exceed 1/10th of an inch. A smooth surface free from tool marks or scratches should be made on the test section of the specimen, and that the change in cross-section from the test portion to the threaded section should be gradual. A one-half inch radius is in conformity to general specifications. By all means a uniform cross-sectional

area should be maintained throughout the gage length of the specimen in order to escape the ever-existing erratic test results.

In operation, the specimen is gripped between the jaws of the machine, Fig. 134, by means of the threaded or toothed vice, with an extensometer, having a sensitivity of 0.0001 inch per inch, attached to the reduced test portion of the specimen with

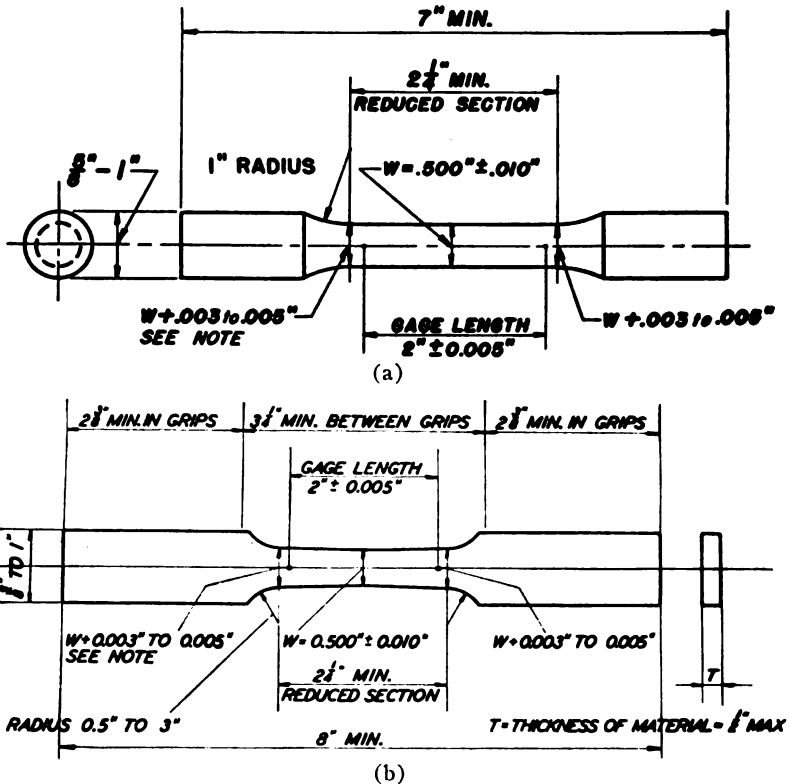
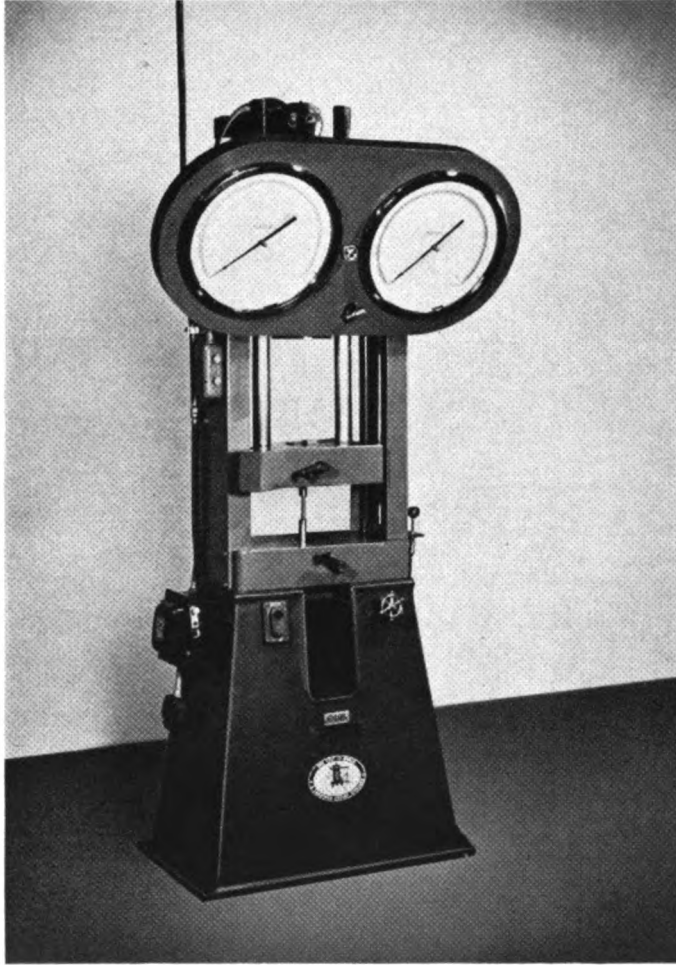


Fig. 133. Standard Round and Flat Tension Specimens.

its dial reading set at zero just previous to the application of the pull. The load is applied gradually and at a constant rate. When a specific extension of the specimen has been reached as indicated by the extensometer dial, the load is suspended momentarily until the extensometer is dismounted from the specimen. At this point, the reading shown on the load dial is taken and recorded in a pertinent report sheet. This reading (yield

load) divided by the original cross-sectional area of the specimen will determine its *yield strength*.

Now, the load on the specimen is increased at a uniform rate



Courtesy American Machine and Metals, Inc.

Fig. 134. The Rhie Tensile Testing Machine.

until the specimen fails. This point represents the *ultimate tensile load*, and when the latter value is divided by the original cross-sectional area of the specimen, the *tensile strength* of the specimen is obtained.

The *yield point* of a given specimen may be determined by several different methods: (1) *Set Method*, (2) *Divider Method*, and (3) *Drop of Beam Method*. All three of these methods may be applied in the testing of a given metal or alloy. In practice,

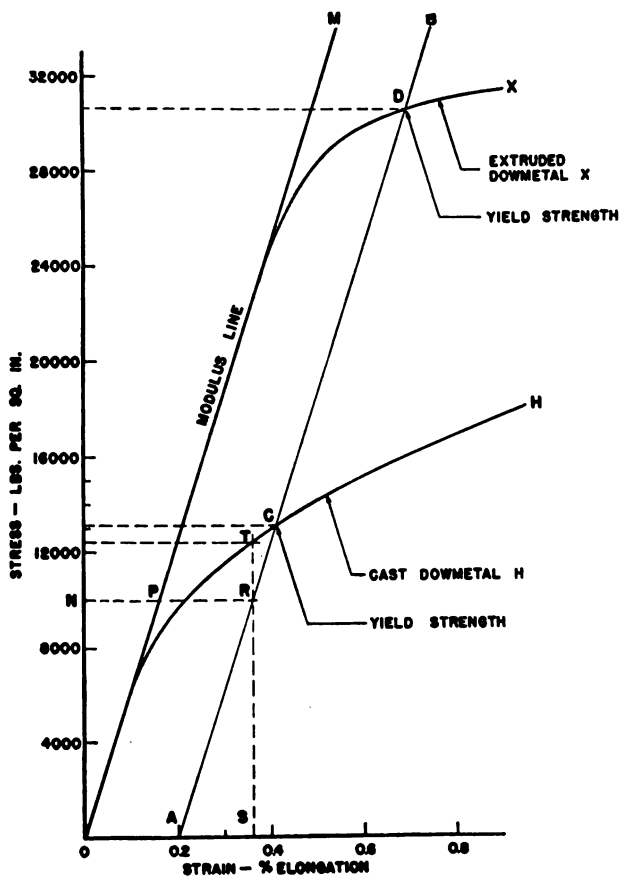


Fig. 135. The Stress-Strain Diagram.

the application of the first method to aluminum alloys, magnesium alloys, and other non-ferrous alloys, and the latter two methods for steel, ferrous alloys, and cold-worked non-ferrous alloys, appears to present decided advantage both in the accuracy of results thus obtained and in the saving of time and labor.

(1) *SET METHOD*.—With the extensometer attached to the

specimen (which, usually has a 2-inch gage length), the load is increased at a uniform rate not exceeding 0.125 inch per minute. Extensometer readings in steps of 0.0002 inch per inch of gage length are taken simultaneously with the corresponding applied loads. The procedure may be extended until an elongation of 0.6 to 0.8 per cent is obtained.

A curve is plotted with the extensometer readings as abscissas against the applied load values as ordinates. This curve is known as a *stress-strain diagram*, whose straight-line portion when extended will constitute the *modulus line*. Parallel to the modulus line, a straight line is drawn connecting the readings taken as 0.2 on the abscissa with that taken for 75 per cent of the prescribed yield strength. The point of intersection of the parallel line and the stress-strain curve, the point *C* or *D* in Fig. 135, represents the yield strength of the material.

In practice, the yield strength of a metal (aluminum, magnesium, brass, etc.) is taken as the stress at which the stress-strain curve deviates 0.2 per cent from the modulus line. That is, the load on the specimen is increased gradually until a permanent set of 0.2 per cent per inch extension has been reached. For a 2-inch gage length, then, the permanent set is obtained with a permanent extensometer reading of $2 \times 0.2/100 = 0.004$ inch. The load value at which this extension has been obtained divided by the original cross-sectional area of the specimen gives the yield strength of the material.

(2) **DIVIDER METHOD.**—Two pin-point marks corresponding to a 2-inch gage length are punched on the reduced section of the test specimen. The specimen, then, is mounted between the jaws of the test machine. One of the points of a sharp-pointed divider, which is set to 2.01 inch (0.005 inch per inch of gage length), is placed in the lower gage mark. The load is applied at a uniform rate until the upper point of the divider coincides with the apex of the corresponding gage mark. The stress at which this occurs is taken as the yield strength of the specimen.

(3) **DROP OF BEAM METHOD.**—With the specimen properly mounted between the grips of the tensile tester, the load is increased at a uniform rate, preferably between 0.5 to 0.1 inch per minute. When the beam of the testing machine drops or the pointer indicates an appreciable halt, the corresponding load

divided by the original cross-sectional area of the specimen will give the yield point of the material. This method is very useful for determining the yield property of wrought iron and steel. It possesses further advantages by saving time and by avoiding possible breakage of the extensometer if the test specimen happens to be defective, which condition may cause the failure of the specimen before the load corresponding to 0.2 per cent permanent set has been attained.

After the specimen fails under tensile load, the two broken pieces are put together and the original 2-inch gage marks are remeasured. The percentage of elongation of the specimen may be obtained by multiplying the total elongation (per 2-inch gage length) by 50.

As the specimen elongates under tensile load, its cross-sectional area becomes reduced. This condition of the material often becomes an index of its mechanical property. Hence, the percentage reduction in area is generally included in the test report. This latter factor may be calculated by taking the difference between the original cross-sectional area and the least cross-sectional area after rupture of the specimen and expressing the value as a percentage of the original cross-sectional area. For instance, a certain steel test bar having a diameter of 0.501 inch and a cross-sectional area of 0.1971 square inch becomes reduced to a diameter of 0.360 inch after rupture under test. The latter diameter is equivalent to 0.1017 square inch. Hence, the difference of the two areas will be $0.1971 - 0.1017 = 0.0954$ square inch. The percentage of reduction in area will be $0.0954 \times 100/0.1971 = 48.4$ approximately.

It is earnestly recommended that all test bars be x-ray inspected previous to subjecting them to the pulling test, as imperfections such as gas-holes, shrinkage fissures, excessive dross, and other inclusions which may or may not cause stress concentrations but will affect the true value of the tensile strength of the material. As was mentioned above, the presence of these defects may further cause the failure of the specimen before the extensometer reading is completed, and this will inevitably cause the destruction of the extensometer.

5. The Effect of Temperature on the Physical Properties of Metals.—When the temperature of a metal is raised the

interspace between the atoms composing it becomes larger in proportion to the temperature. At a suitable temperature, the atoms may become so separated that the metal begins to yield under comparatively small stress. A given stress which at room temperature may only cause an elastic deformation whereas at higher temperatures it may produce a plastic deformation. Hence, in general, the hardness and the tensile strength of a metal are inversely proportional to the temperature, whereas ductility varies directly with the temperature. Temperature also affects the yield point in that the higher the temperature the lower the point at which the metal will begin to yield, and this point becomes extremely low at high temperatures.

The effect of heating of cold-worked metals is indicated in the removal of the internal stresses, recovery of elastic properties of the metal, with increase in conductivity and magnetic characteristics in the case of iron or steel. Recrystallization so as to permit the recovery of any deformation or the distortion of the slip planes with the resultant decrease in the internal energy will cause the formation of nuclei of stress-free crystals, the number of nuclei thus precipitated being directly dependent on the existing deformation and on the temperature at which the metal is annealed. In the case of hot-worked metals the hardening and softening will occur simultaneously. Depending whether or not the deformation has taken place more rapidly than softening, either hardening or softening will occur respectively. Since this phase of the subject will be considered more fully in a later section, the present introductory discussion to heat treatment of the metals will have to suffice tentatively.

6. Constituents of Alloys.—A glance at the periodic chart of the chemical elements will reveal that there are about seventy elements which are considered as metals, of which only about one-half are important commercially. These metals may exist in any of the three distinct states or phases—solid, liquid, or vapor—depending on the temperature of the material and to some extent on the atmospheric pressure. A metallic element may be distinguished from other elements by its luster and ability to conduct electric current and heat. In an electrolytic solution, a metal exhibits an electropositive characteristic, as when ionized it becomes a positive ion of a magnitude dependent

on the number of its valency electrons. Elements which possess the physical characteristics of a metal but chemically behave both as metal and non-metal are known as *metalloids*. The term applies to elements such as carbon, sulphur, phosphorus, silicon, and manganese which in small amounts are present singularly or in multiplicity in the alloys of iron, aluminum, magnesium, copper, nickel, etc. Non-metallic elements such as nitrogen, oxygen, chlorine, bromine, and iodine also occupy a special place in the study of the metallurgical aspects of alloys.

A pure metal has definite temperature factors at which a phase change may occur. For instance, pure copper has a melting point of 1083°C . but when alloyed with aluminum and iron (Ampco metal) the fusion occurs at 649°C ., whereas an alloy consisting of 60% copper and 40% nickel (constantan) will possess a melting point of 1280°C . It is then evident that the addition of a second or a third metal will alter the physical and chemical properties of the pure metal. In the above illustrations the presence of the foreign metal in copper has caused the occurrence of a phase change (to liquid form) either at lowered or elevated temperature compared to the fusion temperature of the original pure metal. We shall presently note that even after solidification of two or more metals in alloy form further changes in phase states will occur though rather slowly. Two or more pure metals when mixed in the molten state and allowed to solidify, marked changes in the crystalline state will occur, and the transformation product is known as an *alloy*. The latter transformation is of particular importance from the viewpoint of metal industry in general.

One peculiar characteristic of an alloy resides in the ability of its constituents to dissolve in each other in the molten state to form a solid solution when solidified. For instance, copper will dissolve in gold in any proportion but will fail to enter into any combination with iron or nickel. This state is rather dependent on the lattice structures of the prospective alloy metals, on the degree of closeness of their melting points, and on the affinity of unlike atoms to each other with a tendency to combine. Such a composition will retain the metallic properties of the original elements. Moreover, the solid solution forms a harder metal than the solvent metal when pure, and if heated to a high temperature

differential vaporization will occur whereby the constituents can be separated.

Pure metals serve very useful purpose in capacities such as electrical conduction as by copper or aluminum wires, or corrosion resistance offered by iron, aluminum, gold, zinc, cadmium, and tin, or the efficacious photoemissive properties of the elements such as sodium, potassium, cesium, etc. But, for purposes of physical and mechanical qualities as required in engineering practice, alloys of metals occupy significant place from the standpoint of tenacity, strength, elasticity, complete resistance to corrosion (such as stainless steel), durability, and service life.

The character of solidification of an alloy chiefly determines its metallographic properties. But, the latter qualities may be followed by alterations in the crystalline form and in microstructures representative of the conditions to which the metal in solid state is subjected. Some alloys are very simple structures, usually of solid solution form, with single primary constituent. These possess the properties of the alloying elements and represent either the average of the original properties or modifications associated with their grain size and orientation, dispersion characteristics, and intermetallic compound constituents. These may be explained further by stating that when a single-phase state exists the composition of the alloy may approximate the interacting pure metal, or, if an intermediate compound is also present its composition will resemble a chemical compound of fixed proportion, all such constituents conforming to the lattice relations of the metals involved. Finally, and most important from the standpoint of foundry practice is the rate of nucleation closely associated with the rate of cooling. The slow rate of cooling of the metal from liquid state produces a minimum rate of nuclei formation with resultant large grain size, whereas a rapid rate of solidification is conducive to finer grained aggregates, provided the procedure is not interfered by the occurrence of polymorphic changes in the metal or alloy.

As further regards to final grain size of the material, when polymorphic granulation is brought into predominance whereby new sets of crystalline forms are created from the primary crystals, the pre-existing crystalline state acquires a new form in which a transformation in the physical characteristics of the

grain structure not independent of the original grain dimension occurs. Such a process is known as *recrystallization*, which inception is closely allied to the process of *nucleation* from crystalline centres in the pre-existing granular aggregates. This transformation may be brought about by thermal treatment, in which the solid matter is subjected to a temperature or temperatures just below that which will cause plastic deformation, to regulate and control the properties of the alloy.

In the case of steel, finer grain aggregates may be produced by treatment with strong deoxidizers, such as titanium, zirconium, and aluminum in association with sodium, silicon, or manganese. Such a process of grain refining may be attributed to the accelerated rate of nuclear formation or to the retardation of the rate of the grain growth. Though coarse-grained steel is important from the standpoint of easier workability, economy of machining operations, and of high temperature service, the mechanical properties including toughness, strength, and case hardened qualities are obtained from fine-grained metals.

Empirical data on foundry castings indicate that metals poured at high temperatures will consist of a coarser-grained structure than those cast at relatively lower temperatures. The effect of temperature becomes further evident by the solidification processes in which gradual cooling of the melt down to the critical temperature will cause an increase in grain size, and below the latter temperature range no further perceptible change in grain size will occur. In annealing, the dimensions of the grains will be small when sustained near the critical temperature, but beyond this the grain will begin to grow until the melting temperature is reached. This growth in the grain size above the recrystallization temperature will principally depend upon the temperature range and to some extent upon the time of annealing. With hot-worked metals, finer grain structure with superior qualities to those obtained from castings will result with gradual lowering of the temperature down to the critical point. Hence, the reason why hot-worked or forged products are found to possess preferable qualities in general to many types of castings.

The mechanism of grain growth involves the tendency of the metal to attain lower energy states than those produced by recrystallization process, in which the metal is relieved of its in-

ternal stresses with simultaneous refinement in its grain structure. Consequently, the newly formed grains are still bounded by a large area and are under the influence of high internal energy. However, as a result of grain growth at the expense of the internal energy, the grain boundary becomes smaller. This causes the boundaries of the larger grains to augment by further reducing the boundaries of the smaller grains of high surface energy distribution with consequent lower stability. As a result, the attenuation of the smaller grains is carried to such an extent that they finally disappear replaced by larger grains grown by the substance of the disappearing smaller grains. The metal then is in a state of normalcy with the intercrystalline residual energy distribution at the lowest state.

(a) *Constitutional Diagrams of Alloy Systems*.—It has been already stated in an earlier occasion that the structural form of an alloy and the character of its constituents are intimately associated with the manner of solidification of the molten metal. That is, when a transition from a molten state to one of solidified state occurs at a rapid rate the resultant alloy will have a fine-grained structure, whereas when the change is slow this structure will essentially consist of a coarse-grained pattern. The importance of grain pattern has also been already emphasized in that the mechanical properties of the alloy will be directly influenced by its crystal structure.

In order to study the behavior of a pure metal or of an alloy system under various temperature conditions ranging from liquid to solid state, graphical representations known as *constitutional diagrams* (or, *equilibrium diagrams*) which show the states and compositions of all possible alloy forms at various temperature values are made available. Such a chart contains experimentally determined data pertaining to changes in the constitution of an alloy, or, a system, with varying temperatures. The horizontal line, or the abscissa, of the diagram represents the composition of the alloy whereas the vertical scale represents the temperature axis.

For binary alloy systems (to which our present discussion on alloy systems will be principally confined) such as the one shown in Fig. 136 for bismuth and cadmium, the diagram contains two curves, *AO* and *BO*, each extending from specific points on the

opposite axis of the temperature scale and representing the temperatures at which all possible alloy compositions of the given metal begin to solidify. The curves are known as the *solidus lines*.

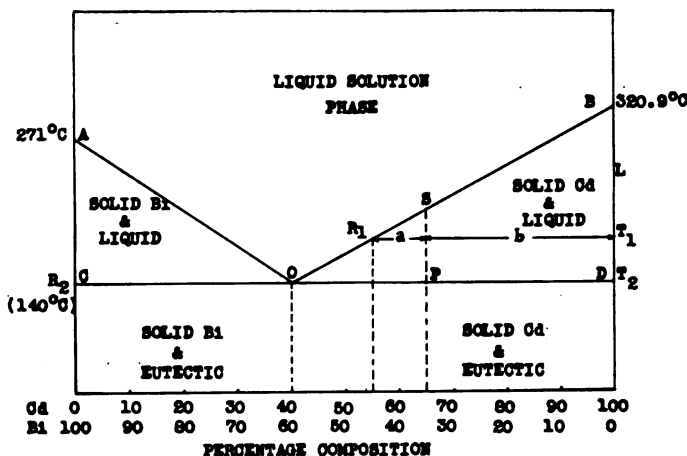


Fig. 136. The Constitutional Diagram of Bismuth-Cadmium System.

Parallel to the horizontal axis is a straight line curve COD which connects all the points depicting the temperatures at which solidification has just become complete when the alloy is cooling, or the melting has just started if the alloy is being heated. This curve is called the *solidus*, below which the alloy is a solid. The two descending liquidus curves of the component metals of the binary alloy intersect at some point O on the solidus line known as the *eutectic point*, at which the alloy of specific composition is known as the *eutectic alloy*, and the temperature at which it occurs is called the *eutectic temperature*. The various distinct areas bounded by these curves are called *phases*, which represent the changes undergone by the alloy system. These curves are of great importance in the quantitative determination of the alloying possibilities of two or more metals, the mechanical behavior of the alloy series, and the character of the alloy as a result of heat treatment.

In the above illustration, the binary system consisting of bismuth and cadmium is a simple case in which the Bi-Cd alloy

is a mechanical mixture in solid state and a solution when in a liquid state. At these various temperature states the alloy comprises physically distinct, homogeneous portions known as *phases*. If the component metals are completely miscible in the liquid state we have one liquid phase. Below the liquidus curve where one of the metals crystallizes in the presence of the melt, another phase is formed; and, the final solid alloy which forms below the solidus line constitutes another phase. The number of phases which may exist in equilibrium under a given temperature (and pressure, if gaseous state is also of concern) may be determined by a reference to the principle known as *Gibb's phase rule*.

The constitutional diagram for a given alloy indicates the true equilbral condition between the constituents at any selected temperature. Furthermore, when one of the two-phase regions is considered, its chemical composition at any selected temperature may be determined by noting the point of intersection made by an exploring line drawn parallel to the eutectic axis with the liquidus curve considered, the properties of the phases present being a function of the entire alloy. In using the diagram, assumption may be made that an alloy may be brought into an equilibrium condition at any selected temperature and retain this structure subsequent to quenching. In practice, the first assumption is correct with reservation, but the second must be considered significant only to the extent that some change, of however little importance, occurs in annealing as a result of rapid quenching, especially when high-temperature treatment is applied.

Further provision for determining the correct temperature for the thermal treatment of the alloy is indicated by the two-phase curves dictating the selection of the temperature to effect the desired constituents of the alloy. So that such a process may meet with success, the operation must be conducted accurately and within close limits of the temperature gradient of the quenching medium. Even then, complete retention of a particular structure, which may be stable at high temperatures, can not be practicably realized—a significance why commercial alloys in general do not bear true equilbral state.

Aside from indicating the presence of phases, the equilbral conditions in the constituents of the phase systems, and the

relevant changes, a constitutional diagram further reveals the proportions of the phases or constituents present at a selected temperature, provided the true composition of the alloy under consideration is known.

(b) *Interpreting Constitutional Curves.*—Referring again to Fig. 136, the composition of the alloy shown is 60% bismuth and 40% cadmium, and since it is a eutectic-forming alloy it will freeze at a constant temperature, namely 140°C. Furthermore, as the percentage of bismuth increases from 0 to 60% it lowers the freezing temperature of cadmium correspondingly. Similarly, as cadmium percentage in the alloy is increased toward 40%, the freezing point of bismuth will be correspondingly lowered. It is obvious then that the two alloying metals alternately become a solute and a solvent for each other.

If the two-phase alloy consisting of 40% cadmium is cooled from 320.9°C. to a temperature T_1 , the composition of the liquid phase will be indicated by R_1 . In order to obtain a quantitative measurement of the two phases, a vertical line NS is so erected from the abscissa that it passes through point P representing the total composition of the mixture. If now T_1 and R_1 are joined by the horizontal lines a and b , the point of intersection on the vertical SN may be considered as the fulcrum of a beam R_1T_1 . The quantity of each solid phase and molten phase in this area, then, will be inversely proportional to the relative lengths of the lever arms represented by a and b . Thus, at temperature T_1 the relative amount of solid cadmium varies from 0% at R_1 to 100% at the boundary line L , and the percentage of the solid at temperature T_1 will be given by the equation

$$\text{Per Cent Solid Cadmium} = \frac{a}{a + b} \times 100 \quad (118)$$

$$\text{and,} \quad \text{Per Cent Liquid} = \frac{b}{a + b} \times 100 \quad (119)$$

where, the numerical values of a and b , which are read from the composition base line, will be 10 and 35 respectively.

Therefore, by substituting the respective quantities in equations (118) and (119), we obtain

$$\text{Per Cent Solid Cadmium} = \frac{10 \times 100}{10 + 35} = 22.22\%$$

$$\text{Per Cent Molten Metal} = \frac{53 \times 100}{10 + 35} = 77.77\%$$

By the same analogy, the ratio of the solid bismuth and the molten metal may be calculated by using equations (118) and (119) at any selected temperature.

When the entire alloy is cooled to the eutectic temperature T_2 (140°C.), where solidification of all the constituents becomes complete, the fulcrum arm a will assume the length CO , and that b will assume OD . Hence, the composition of the solid *Bi-Cd* alloy will be

$$\text{Solid Cadmium} = \frac{a \times 100}{a + b} = \frac{40 \times 100}{40 + 60} = 40\%$$

$$\text{Solid Bismuth} = \frac{b \times 100}{a + b} = \frac{60 \times 100}{40 + 60} = 60\%$$

Equilibrium diagrams for other alloys of more complicated composition may be constructed in this manner and the amount of each constituent can be calculated by means of the above formulas using the same method as in the above example. There are, however, other means of calculating the exact quantity of each of the constituents present, but the scope of this book does not permit to extend the discussion. One easy way of determining to an approximation the amount of each of the eutectic and the solid solution is to take an enlargement of the photomicrograph of a given specimen and to measure the relative areas of the solid solution and the eutectic. Then, by taking the solid-solution equivalent of the eutectic and comparing it with the amount of the solid solution, the relative weights of the two constituents are found.

(c) *Gibb's Phase Rule*.—This rule applies only to conditions of complete equilibrium in alloy systems (though this is rarely realized); and, in so doing, it predicts the number of phases that may exist in an alloy system under definite values of the temperature, pressure, and the volume. Assuming that in a given alloy under selected temperature and pressure there are P phases in the region bounded by the temperature ordinate, the liquidus

curve and the solidus curve. If in the system of this region there exists C components, then the degrees of freedom (change in temperature, pressure, and concentration) of the system may be given as

$$F = C - P + 2 \quad (120)$$

in which, F represents the degrees of freedom or the variables of the phase P , and C stands for the number of components that exist under the given set of conditions.

For example, in the field between the liquidus and the solidus curves shown in Fig. 136 the number of phases present will be given as 2—one is the liquid, and the other the solid metal, either bismuth or cadmium. The number of components present will be 2, as there are only bismuth and cadmium atoms present. Hence, according to equation (120), the possible degrees of freedom that may exist will be given by

$$\begin{aligned} F &= C - P + 2 \\ &= 2 - 2 + 2 \\ &= 2 \text{ degrees of freedom.} \end{aligned}$$

Since the amount of gaseous state that may exist in this region is very small, we have neglected the vapor phase, and consequently the pressure, thus reducing the variables to the concentration and temperature of the system. If the pressure is limited to atmospheric state (approximately 1 atmosphere under ordinary conditions) then any change in the temperature of the system will effect a corresponding change in the concentration of each of the phases. Thus, at the eutectic temperature, at which there are two solid components and one liquid, the degrees of freedom that will exist may be given as

$$\begin{aligned} F &= C - P + 2 \\ &= 2 - 3 + 2 \\ &= 1 \text{ degree of freedom,} \end{aligned} \quad \begin{array}{l} \text{where, } C = 2; \text{ Cd and Bi.} \\ P = 3; \text{ Cd, Bi, and} \\ \text{liquid.} \end{array}$$

in which, if the pressure is fixed to 1 atmosphere, as stated above, the condition is fulfilled, and any change in the temperature or concentration of the system will cause one of the phases to disappear.

7. Thermal Treatment of Metals.—The process involving the heating and cooling of a metal or an alloy to regulate and control its properties is known as *thermal treatment* or *heat treatment*. There are various methods of heat treatment, but in general they all serve practically the same purpose. The operation usually consists of heating the metal or the alloy to its critical temperature in order to cause a change in the internal structure of the material. Since castings that have been solidified under inconsistent temperature conditions and those metals that are work hardened generally exist in a state of high internal energy, sometimes this is associated with localized stress concentrations in the castings. The condition may be brought to a stable state if the atoms are given freedom to move to a stable or low energy state. This may be accomplished by heating the metal so that its interatomic spacing is increased with resultant mobility imparted to the atoms under unstable and stress states. The mechanism involves the recovery of the lattice structure, and the rate at which such a relief occurs is dependent on the temperature and on the time of heating. In thermal treatment of steel, the process effects a fundamental change in the crystalline structure of the metal; and, in annealing, it merely serves to correct or remove the undesirable properties of the material. Heat treatment, indeed, thus becomes a normalizing procedure for these types of materials.

Thermal treatment principally serves to harden the metal or to increase its tensile strength; and, in the case of castings, the process relieves the internal stresses; to anneal materials by removing stress, inducing softness, and to refine the crystalline structure, or alter in general the physical properties of the material; and, to carburize the surface of steel by impregnating it with carbon in the presence of carbonaceous derivatives, or to nitride it with nitrogenous materials.

Recrystallization of the crystalline structure plays an important role in affecting the physical properties of the metal. This may produce either grain refinement so desirable in aluminum sand castings, or grain growth as in annealing work-hardened metals for the purpose of softening them for machining purposes. On the other hand, the procedure also seems to bring about the solution of those components still in isolated state or to cause the

precipitation of the intermetallic compounds which in some types of castings appear to be very desirable from a standpoint of producing added strength in them.

The factors involving the process of thermal treatment comprise (1) heating the metal to the critical temperature, or, in some cases to a temperature just below its fusion point, (2) sustaining this temperature for a predetermined interval of time in a suitable medium such as gas (steam or air), or liquid such as water, saturated solution of a salt chemically inert to the metal concerned, or in a medium of oil or a molten salt such as sodium nitrate, or molten metal such as lead; and, (3) cooling or quenching the substance by bringing it in contact with an inert gas, liquid, or solid. In every one of these operations, the temperature and the time of treatment during individual processes are of consequence from the standpoint of microstructural control. Latest methods of thermal treatment, however, make use of radio-frequency induction methods whereby the metal under consideration is placed between the terminals of a high frequency generator which causes a spontaneous intrinsic heat in the metal without affecting the furnace walls which are of non-conducting material.

The operation of heat treatment may be carried out in an open furnace with the flames in contact with the object under treatment, or it may be conducted in a high-frequency electric muffle. A further procedure is, as mentioned above, to immerse the material into a molten bath or, if the material does not produce an alloy combination with lead, it may be immersed into molten lead. Molten baths are preferable, if the procedure permits, since the heating of the object takes place more rapidly and the temperature distribution is very uniform throughout its substance. Heavy electric currents sometimes passed through the object for the purpose of heating it do not seem to give satisfactory results owing to uneven distribution of heat, as the interior of the metal becomes hotter than the surface, and the action is rapid. Such a procedure causes warping or cracking in the metal thus treated. Thus, the rate of heating is limited by the thermal conductivity of the object treated. Externally applied heat will produce heating from the surface inward. In the case of an electrically heated furnace, the heating spreads

from inside outward producing at times a temperature gradient undesirable to a successful treatment.

To realize a particular purpose in the thermal treatment of a metal, accurate control of its temperature is prerequisite. This is accomplished by the character of the medium bringing forth the desirable heat conditions. Furnace atmospheres consisting of nitrogen, carbon dioxide, water vapor, or hydrocarbons are suitable to some types of materials, while in others they produce deleterious effects by combining with the material to form oxidation or carburizing products, as in steel. Nitrogen, although neutral toward most metals, becomes a chemically active ingredient in presence of magnesium at temperatures above 750°F. Hydrogen is a reducing agent, and hence its application in the heat treatment of copper will cause the removal of the cuprous oxide from the grain boundaries of the crystalline structure, resulting in a weakening of the metal. Steam at 300°F. may be employed in the thermal treatment of aluminum alloys to cause the precipitation of the intergranular components. Generally, the atmospheric temperature in a heat treating furnace having a gas medium ranges up to 2500°F.

Salt baths used as a medium for thermal application may be classified into three groups: (1) Low temperature baths, which include sodium nitrite, sodium nitrate, and potassium nitrate. The temperature range of these baths varies from 250°F. to 1100°F. Baths within these temperature ranges are employed for precipitation treatment of aluminum alloys, or bluing steel, and for quenching low alloy steels. (2) Medium temperature baths consist of chlorides, or a mixture of chlorides and carbonates. The latter bath may be used at temperatures slightly above the melting point of the carbonate and up to 1600°F. in the normalizing and hardening of steel, and in the treatment of non-ferrous metals such as bronze, copper, nickel, nickel-silver, brass, etc. (3) Baths that are used in the high temperature range, from 1800°F. to 2400°F., comprise a mixture of borax, sodium fluoride, and barium chloride, and glass baths such as silicates and limes. The application of the process at the above temperature range is confined to hardening high speed steel and tool metals.

Of the liquid baths the use of molten lead at temperatures

between 650°F. to 1759°F. is advantageous to the extent that heat distribution is rapid and more or less uniform. But, owing to the high density of the metal, objects immersed in it should be held down firmly to avoid floating, which latter event may militate against the advantages offered by the procedure.

Some useful salt baths, their composition, and their working ranges proven to render satisfactory results, are given in Table XII, below.

Table XII:—SALT MIXTURES, THEIR COMPOSITIONS, AND MELTING POINTS.

Mixture		Melting Point °F	Working Range °F
Component	Percent By Weight		
Lithium Nitrate Potassium Nitrate Sodium Nitrate	23.3 60.4 16.3	250	270—600
Lithium Chloride Potassium Chloride	45.0 55.0	666	700—1100
Barium Chloride Calcium Chloride Sodium Chloride	31.0 48.0 21.0	806	880—1300
Potassium Chloride Sodium Chloride	56.0 44.0	1220	1300—1500
Sodium Chloride Sodium Fluoride	72.6 27.4	1247	1350—1500
Barium Fluoride Calcium Fluoride Magnesium Fluoride	70.0 15.0 15.0	1454	1550—1700
Barium Chloride Barium Fluoride	83.0 17.0	1551	1650—1850
Water Oil	.... ....	.... ....	Up to 212°F Up to 500°F

Subsequent to heating the material to the required temperature for the desired interval of time, it is removed from the heating furnace and is subjected to rapid cooling by immersing it into a quenching fluid such as a blast of air, water, or oil, or successive

combination of these, depending upon the character of the material and its physical properties such as its specific heat, thermal conductivity, surface conditions, and on the temperature at which the object has been emerged from the thermal treatment.

The character of cooling has definite bearing on the mechanical properties of the material, producing partial softening as a result of recrystallization of the metal. For some metals the process must be carried out very rapidly, as for precipitation-hardening alloys such as "*K*" *Monel* and "*Z*" *Nickel* alloys. For steel, cooling must be conducted very slowly, and for high nickel alloys and for copper the procedure may be either slow or rapid. The rate of cooling is also a function of the quenching medium, and, therefore, discretion should be exercised in the selection of the proper medium. Moreover, to obtain the greatest efficiency of the cooling medium, it must be allowed to come in intimate contact with all the parts of the object treated, and preferably the medium should circulate in order to carry away the heat from the metal as fast as the transfer of heat to it.

It should be kept well in mind that unless the quenching procedure is conducted under most carefully predetermined and controlled conditions the thermal treatment will be of no value, since the manner by which the metal is cooled will largely determine its mechanical properties which are mainly sought in this process. Many a sound metal object subsequent to heat treatment has produced weakness, crack, grain growth, and other anomalies during quenching that it has become worthless as an article of manufacture. Most of the cracks that are produced during machining can be traced down to thermal processes.

8. Pyrometry In Foundry Practice.—Accurate control of temperature in metallurgical processes comprising refining, casting, thermal treatment, and smelting, should be considered as fundamental. Frequently, inferiority in quality of the material may result from indiscriminate observance of the temperature which may have had a variation of 15° to 25°F. from that normally required. For rough estimation of temperature, especially that of steel, a simple scale arrangement by Howe presenting different colors for various temperatures of the metal is given in Table XIII.

The results derived from such a scale is rather limited owing

Table XIII:—COLOR-TEMPERATURE SCALE FOR METALS.

Color	Degrees Fahrenheit	Degrees Centigrade
Lowest Visible Red	887	475
Dark Red Heat	1022 - 1157	550 - 625
Cherry Red	1292	700
Bright Red Heat	1562	850
Orange	1652	900
Yellow	1742 - 1832	950 - 1000
Incipient White Heat	2102 - 2372	1150 - 1300
White Heat (Incandescent)	2552 - 2822	1400 - 1550

to the differences of individual perceptions and judgment of colors. Though empirical foundry practice in early days had to rely on this type of temperature determination, the results obtained by persons experienced in the art were within reasonably correct range compared with late mechanical or electrical temperature-indicating devices.

In general metallurgical practice, mercury or alcohol thermometers are not of much importance, if any, owing to the relatively high temperature ranges at which such metallurgical work is carried out. Therefore, thermoelectric devices known as *pyrometers* are employed, since their range of use extends up to 3000°F., close to the melting point of platinum. Such a device consists of (1) a thermocouple, (2) an indicating instrument for measuring the electromotive force, which value when calibrated gives direct temperature readings, and (3) two leads joining the thermocouple to the measuring device. Frequently, the electromotive force produced by the thermocouple is amplified by means of an electron tube before being led to the temperature-indicating apparatus.

The thermocouple consists of two wires of dissimilar compositions so that when they are brought together to make an intimate contact, as by welding, and then subjected to temperatures above normal, electrons will be released from one metal and flow into the other by way of the indicating instrument when a closed circuit is established by a series contact. The number of electrons released is a function of the temperature of the junction where the two unlike wires meet. The free ends of the thermocouple are connected to a galvanometer whereas the welded junction,

where the two metals are in intimate relation, is usually inserted into the system whose temperature is to be determined. This junction is then called the *hot junction*, and the terminals are known as the *cold junctions*, since they are kept usually at atmospheric temperatures.

The thermocouple elements may be made of platinum *vs.* an alloy consisting of platinum 90% and rhodium 10%. The two leads are insulated from one another by a suitable refractory material such as porcelain or Mullite. For prolonged operations a maximum temperature of 2500°F. is permitted, while for intermittent use 3000°F. Another couple may be formed by means of chromel and alumei wires insulated in Mullite. The temperature

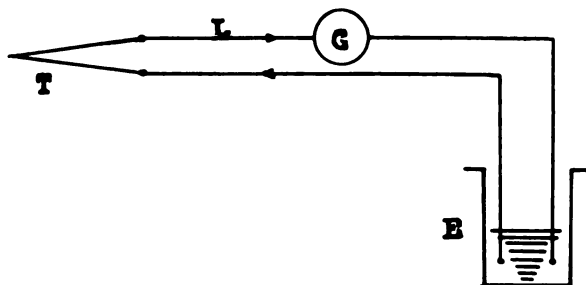


Fig. 137. Diagram of a Simple Thermoelectric Pyrometer.

range for this couple is 2000°F. for prolonged use, and 2400°F. for intermittent use. Still another couple may be produced by the union of iron and constantan wires, whose temperature range for continuous work is 1600°F., and for intermittent use it is 2000°F.

In operation, the thermocouple is inserted into the molten metal, hot furnace, or into any other object whose temperature is beyond the range of a mercury thermometer. When the indicating dial is adequately calibrated, direct temperature measurements can be secured from the instrument.

A simple circuit diagram illustrating the principle of operation of a thermocouple is shown in Fig. 137. A galvanometer *G* is connected in series with the thermocouple *T* through one of the leads *L*, and the circuit is completed at the cold junction *E* which is placed in a well in the ground. When the thermocouple

is inserted into the medium whose temperature is to be measured, the galvanometer will register the amount of voltage in millivolts equivalent to the heat energy content of the system.

Another type of pyrometer which operates on the potentiometer principle employed in a bridge circuit is shown in Fig. 138. A primary source of electromotive force consisting of a dry cell or a storage battery B is connected across a fixed resistance R_2 and a variable potentiometer resistance R_1 through a series protective

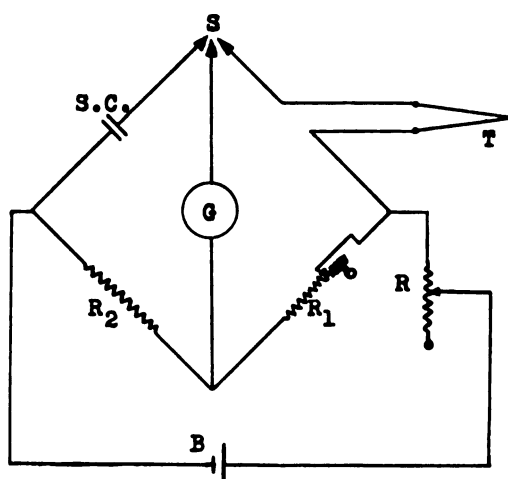


Fig. 138. Diagram of a Pyrometer Circuit of Potentiometer Arrangement.

resistance R . A standard cell $S.C.$ furnishes a specific amount of $E.M.F.$ and is so connected in the circuit that its $E.M.F.$ opposes that furnished by the battery B when the switch S closes the circuit containing the cell.

The rheostat R_1 is so adjusted that the potential drop across it is equal to that in section R_2 . This is indicated by the zero deflection of the galvanometer with the switch S closing the circuit to $S.C.$ In taking temperature measurements, the switch S is turned to the thermocouple point, and with the thermocouple properly inserted into the medium whose temperature is to be determined the position of the slide wire is adjusted until no deflection is noted on the galvanometer. This means that the $E.M.F.$ produced by the thermocouple is exactly equal to the

voltage drop in the slide wire represented by R_1 . The circuit is then balanced and no current flows through the galvanometer. Since the deflection is directly proportional to the thermocouple $E.M.F.$ and hence to the temperature of the medium considered, when the slide wire section is calibrated, direct temperature readings may be obtained from it. However, frequent adjustments should be made with the standard cell, since the voltage of the battery B diminishes by use.

Other types of pyrometers that are extensively used commercially at temperatures above 3000°F. are the *optical pyrometer*, and the *radiation pyrometer*. Since space does not permit a discussion of these instruments and in view of excellent texts fully covering the subject, only mention as regards the former pyrometer together with a discussion of its principle will be given here.

An optical pyrometer essentially represents a type of photometer in which a limited range of the visible spectrum consisting of monochromatic wavelengths in the neighborhood of 6500 angstroms is used to compare the intensity of radiation from an incandescent body emitting similar radiation.

In operation, a telescope arrangement is sighted upon the incandescent body whose temperature is to be determined. Upon the focus of this image is superimposed the beam of light from the standard comparison source calibrated in terms of the black body temperature at 1063°C. , the freezing point of gold. A photometric match is brought about by varying the brightness (temperature) of the comparison source, and direct readings are made by consulting pertinent calibration charts.

The basis for the optical pyrometry resides in the distribution law formulated by Wien and Planck. This law states that the amount of energy radiated by a unit wavelength per unit area of a black body is a direct function of the absolute temperature T of the black body and the wavelength λ radiated from it. Putting this quantitatively, we have

$$E = C_1 \lambda^{-5} \epsilon^{-\frac{C_2}{\lambda T}} \quad (121)$$

in which, E is the intensity of the radiation of wavelength λ , C_1 is a constant which is canceled during operation of the equation, ϵ is the base of Napierian logarithms, λ is the wavelength

of the radiation (about 6500 A.U.), C_2 is a constant equal to 14,350, and T is the temperature of the black body in Kelvin scale. The equation is applicable to measurements of temperature up to 5000°C. (approx. 9000°F.).

CHAPTER X

PHOTOMICROGRAPHIC TECHNIQUE

Within the past few years great impetus has been given to the micrographic exploration of the internal structure of metals and alloys in an effort to relate such findings to the physical and mechanical characteristics of the material considered. Such a study is supplemented by the photograph made of the specimen viewed in the microscopic field for permanent record and for further reference. The art of enlarging the microstructure of a specimen with the aid of a microscope and subsequently photographing it is known as *photomicrography*, and the permanent record made on a suitable photographic film or paper is called a *photomicrograph*.

In order to procure an accurate microstructural view, it is of paramount importance that the specimen selected be truly representative of the metal from both physical and chemical standpoints. Furthermore, proper care should be exercised in the preparation of the specimen so that its surface to be examined is polished to a mirror-like appearance and is perfectly flat from center to edge, and contains no scratches or mechanical imperfections as a result of preliminary manipulation and polishing. Preservation of all non-metallic inclusions, intergranular materials, and the natural form of the grain boundaries is particularly essential in the revealing of the microstructure that is both representative and truly characteristic of the metal in order to permit the correct interpretation of all magnifications. To ensure the latter condition, proper selection of the etchant and the technique of its application to the polished surface is of particular consequence.

Microscopic examination of metals not only lends itself to the qualitative analysis and the determination of the grain structure of the material but it also aids the designer, founder, or the manufacturer in general to improve the quality of his product by modifying the composition of his alloy, the process of producing it, and subsequent thermal or mechanical treatment, each of which factors hold direct bearing on the character of the final material.

Microshrinkage and porosity which are well defined and detected in a radiograph can be further studied and analyzed as to their possible injury to the material in service. The shrinkage generally appears at the crystal boundaries, and when in an advanced stage, the micrograph reveals the extent of separation of the grains one from the other. This recession of the grains may be further due to the corrosion of the intercrystalline constituent, which condition when detected in a radiograph will appear identical with microshrinkage.

As stated in an earlier occasion, the percentage composition of an alloy constituent may be determined to a close approximation by a reference to the micrographic view of the specimen magnified to a specific dimension, usually 100 diameter. A quantitative determination by weight of the various constituent structure revealed under the microscope may be made by projecting and photographing the field viewed under the microscope upon a 10" x 12" photographic bromide paper, and subsequently cutting with a pair of fine-edged scissors any particular constituent selected and comparing its weight with that of the total field. This will give the amount of the constituent present by weight within a few per cent accuracy. For instance, if the weight of the micrographic paper representing the total field is, let us say, 25.8 grams, and the weight of the paper containing the selected constituent is 5.16 grams, then the percentage of the material under consideration will be approximately $5.16 \times 100/25.8 = 20$ per cent.

A micrographic view of a given specimen serves a further important purpose regarding the controlling of the concentration of a particular constituent through information derived from an examination of the crystalline structure of the specimen. This is accomplished by a series of heating and cooling processes during which one constituent may partially or wholly dissolve in the other, or, further precipitation may result from the treatment, as the case may be, thus altering the physical and possibly the mechanical properties of the alloy of interest. It can be predicted from the micrograph in conjunction with the constitutional diagram of the particular alloy considered precisely to what extent the resolution, precipitation, or recrystallization (refining, coarsening,

or the orientation of the crystals) of the alloy constituents can be brought about by further physical or mechanical treatment.

1. Preparation of the Specimen.—In the preparation of a specimen for microscopic examination, the sample chosen preferably should be characteristic of the material that has failed in service. It is also advisable that a section of the normal structure of the material be included for comparative study. When making specimens of rolled or forged materials, two sections at right angles to each other (one parallel to the rolling, and the other crosswise to it) should be taken in order to show the extent of fibering, its radial dimensions, and to reveal non-metallic inclusions, if any, present in its structure.

Having selected a proper section of the material for the metallographic examination, it may be cut with a suitable hacksaw preferably lubricated to eliminate the effect of heating due to friction. The importance of the latter operation can not be over-emphasized, as when heat is generated in cutting, the grain structure of the metal will be so altered that the specimen will not be any longer representative of the parent material. Excessive pressure, dragging of the surface, and other deformative manipulations should be invariably avoided, as these will materially affect the microstructure of the metal.

A typical specimen measures about 5/16th inch square and between 1/8 to 1/4 inch in thickness if the metal is to be mounted in a plastic support. There are on the market various types of thermoplastic materials of which Lucite, Plexiglas, Crystalite, Bakelite, Styron, Tenite, etc. will serve the purpose very satisfactorily. Lead, Wood's metal, sulphur, and other thermoplastic alloys of low fusion temperature may be conveniently employed for mounting specimens which are hard to handle due to their small size. If thermoplastic materials are not available, the specimen may be cut from 3/4 to 1 inch square and about 1/2 inch thick so that it can be easily held between the fingers during the polishing process. After the polishing and etching, the naked specimen may be mounted in clay, or sealing wax, and held in a plane perpendicular to the optical axis of the microscope by means of the device shown in Fig. 139.

The mounting of the specimen in a thermoplastic or thermosetting plastic may be accomplished by means of a mounting press

shown in Fig. 140. The apparatus consists of a mold which is made in three parts (shown in the figure). A small cylindrical block on which the specimen is centrally placed is inserted into a tight-fitting cylinder. Between four to six grams of granular lucite or bakelite is carefully poured into this cylinder, covering the specimen completely. A third piece of plunger of larger size than the first block and having a cavity for holding a thermometer is introduced into the open end of the cylinder. The assembly is placed over the square asbestos board mounted on the lower

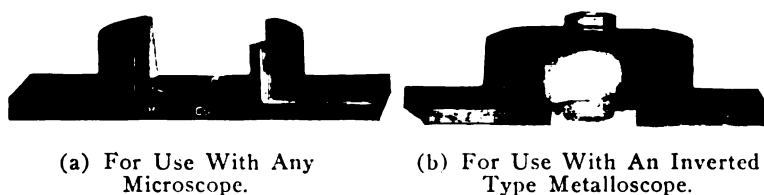


Fig. 139. Micrographic Specimen Holders.

platen of the press. The pressure is applied by means of a long handle which raises the lower platten by hydraulic pressure.

A split-type electric heating block is then placed around the mold, Fig. 141, and the current is turned on to bring the mold to the desired temperature. A pressure of 1100 pounds per square inch is sustained until the temperature of the lucite reaches about 85°C., when the plastic will start to soften. The pressure then is raised to between 3000 and 3500 pounds per square inch, and is maintained at this range until the temperature of the specimen rises to about 125°C. to 130°C., which will take about 10 minutes. Subsequently, the heating block is replaced by the cooling block, which is made of aluminum for carrying the heat away at a rapid rate. When the temperature drops down to about 60°C. or lower, the pressure is released, and the mold is taken out and is placed under the ejecting plunger on the left-hand side of the press. By again manipulating the long handle, the pressure is applied to the plunger, which removes the mount from the mold. The specimen will appear as shown in Fig. 142.

For mounting a specimen in bakelite, the technique is similar to that given for lucite, except that the maximum temperature may run up to 160°C. and maintained for one or two minutes.

For better consolidation of the plastic around the specimen the pressure is sustained at 4000 pounds or over.

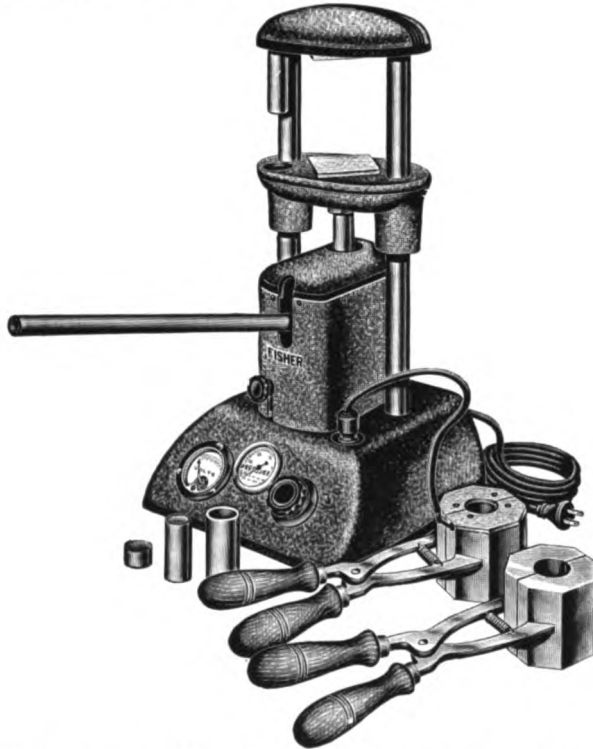


Fig. 140. The Fisher Mounting Press for Micrographic Specimens.



Fig. 141. Manner of Application of the Heating Block to the Press.



Fig. 142. Specimen Mounted In Lucite.

2. Polishing the Specimen.—Subsequent to the mounting of the specimen, it is ground on fine emery cloth of different

grades, or more preferably on an endless belt supported on electrically rotated cylinders, shown in Fig. 143. The belt is coated with an abrasive of aluminum oxide (emery) or silicon carbide

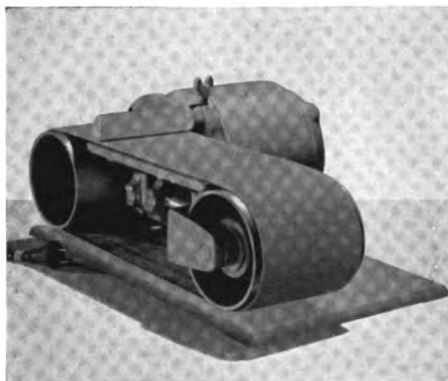


Fig. 143. The Metallographic Grinder.

(carburandum), and the operation is carried on with various belts of increasing degrees of fineness. The final grinding embodies the abrading of the specimen with suitable emery paper of grades

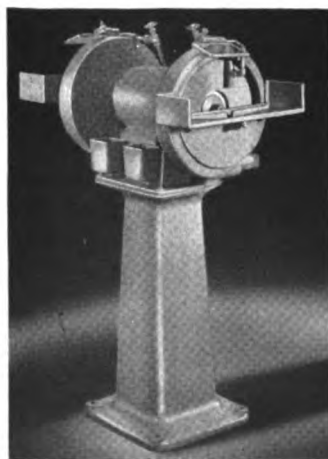


Fig. 144. Metallographic Grinder with Self-Lubricating Attachment.

No. 0, 00, 000, and 000 respectively. It should be noted that on passing from one grade of abrasive to the other the specimen should be rotated 90 degrees, and the abrading should be continued

until all the scratches left from a previous operation has been entirely removed. This is important, because the effect of the scratch lies deeper than the actual scratch marks, and all these invisible impressions should be obviated by prolonged abrading after the marks have disappeared.

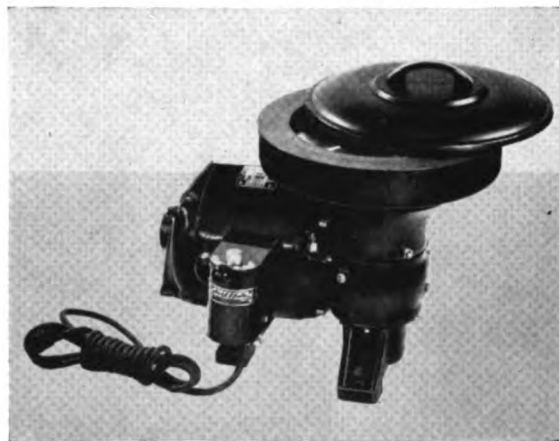


Fig. 145. Metallographic Lapping Machine.

Occasional lubrication of the abrasive with rectified mineral oil diluted with kerosine 1 : 1, or other lubricants such as glycerin, paraffin oil, or soap, will prevent the frictional heating of the specimen and hence will eliminate the tempering effect of this heat. The best method for rough finishing, however, is the application of lead lapping disc, by the use of which preservation of inclusions and elimination of excessive distortion are achieved.

Another satisfactory method in which the inclusions may be preserved intact is by rough polishing the specimen on a paraffin-impregnated cloth and finishing it on silk or velveteen.

When the final grinding or lapping has been performed, the specimen is transferred to a polishing wheel, shown in Fig. 145, covered with a soft cloth of suitable texture such as white duck or fine broadcloth for preliminary and "kitten's ear" or *velveteen* for the final polishing.

In the author's laboratory, an improvised polishing apparatus is devised by mounting two discs, each having a diameter of 8 inches, in a horizontal position and driven by a single 1/4 horse-

power motor. A pulley arrangement in conjunction with a suitable rheostat regulates the speeds of the individual polishing discs. One of the discs rotates at a speed between 400 to 500 revolutions per minute and the abrasive is an aqueous suspension of No. 600 alundum powder. The specimen is held gently against the revolving disc with slight pressure and is moved back and forth at a uniform rate from the periphery to the center of the lap until



Fig. 146. Metallographic Polishing Machine With Detachable Aluminum Polishing Plates.

all traces of scratches left from the previous lapping are removed.

When the preliminary lapping on the polishing cloth is accomplished (which should not take over 10 or 12 minutes), the specimen is washed under running water or preferably with distilled water, after which procedure it is ready for final polishing operation. The second disc, over which an improved type of velvet cloth is snugly fitted rotates at a rate of between 150 to 250 revolutions per minute. The abrasive ordinarily employed on this lap is a water suspension of magnesium oxide, jeweler's rouge, or levigated alumina. This writer prefers relevigated alumina (made by forming a suspension of levigated alumina in distilled

water and syphoning the upper 3/4th of the liquid column) because of its superior polishing character for all types of metals in general, and because the tendency for surface deformations as produced by other abrasive means is very meager.

During the final polishing on either cloth disc, the surface of the pad should be constantly kept wet by the respective suspension dripping from an adjustable flow control. The polishing liquid may be contained in a bottle conveniently mounted above the disc on a support, illustrated in Fig. 146, and may be equipped with a rubber tubing. The flow may be adjusted by hosecock clamp. As polishing proceeds, it is advisable that the specimen be rotated 180° occasionally, and the pressure on it be gradually attenuated. Towards the latter part of the operation, the bottle with the suspension liquid is replaced by one with distilled water, which is made to drip over the lapping pad until the polishing is completed.

Although the procedure of preparation of the specimen appears relatively simple, it cannot be too strongly emphasized that the final examination and accurate interpretation of the structures revealed in the specimen will be dependent largely on the character of the final polishing which requires great skill and, indeed, patience. It is only through continued practice that the scheme of preparing the specimen satisfactorily is mastered. Extreme cleanliness, of necessity, should be exercised by frequently washing the specimen with distilled water, and eliminating all dust and particles of coagulated suspension powder from the polishing cloth.

The surface of the finished specimen should possess a mirror-like appearance, perfectly smooth, and free from any traces of even the finest scratches. This may be examined under the low power lens (about $\times 10$), and if any defective polishing is indicated, the specimen should be repolished on the final lapping cloth which has been previously washed thoroughly with distilled water and freed from foreign particles of any character.

When the desired degree of polishing has been obtained, the specimen is washed with distilled water to remove all adhering abrasive particles from its surface. It may then be rinsed in warm ethyl alcohol and thoroughly dried under a warm current of air furnished by a specimen dryer such as shown in Fig. 147.

In the event that such a dryer is not available, the surface of the specimen after having been rinsed in the alcohol may be dried by blowing vigorously on it. Care should be taken that not a single particle of the saliva from the mouth lights on the specimen, as the liquid will have an etching effect especially on metals of non-ferrous type such as aluminum, magnesium, zinc, etc. It will be further advisable that etching should immediately follow the final polishing to avoid possible oxidation or tarnishing of the surface of the specimen.



Fig. 147. Electric Specimen Dryer Furnishes a Blast of Warm Air to Dry All Four Faces of the Specimen.

3. Etching the Metallographic Specimen.—The polished and dried specimen should be first examined with the microscope before an attempt is made to etch it. This view of the specimen is of particular benefit in that certain types of non-metallic inclusions, surface flaws, graphite in cast iron, the character of the surface structure, and the possible presence of other unsuspected anomalies are often readily observable and may be compared with the etched surface.

Frequently, when the surface of the specimen is illuminated by an oblique beam of light, certain hard constituents of the alloy stand out in relief. Cracks and microporosity due to shrinkage stand out visibly, and after the specimen is etched these are not confused with darker dendritic structures or eutectic constituents. In most cases, the structure of the matrix is not clearly defined prior to etching, and occasionally the true structure of the

metal is obscured by a layer of surface disturbance, which consists of an amorphous film of the metal smeared homogeneously by the electrolytic action of the different constituents of the surface metal. This layer, however, is entirely cleared by being dissolved in the etchant during the etching process.

In order to reveal the structure of the polished specimen it must be first etched in a suitable etching solution. The etchant usually begins to act first on the grain boundaries, thus revealing a system of polyhedral grains as a result of differential action of the reagent. The purpose of the etching solution is to act on some constituents to a greater extent than on others, producing a contrast that the differentiation of the entities present is made possible. Furthermore, different metals or different alloys will have to be treated in a type of etchant that is more suitable for the specific constituent which is desired to be studied. For instance, a dichromate etchant can not be used on an aluminum specimen with the same success as when it is employed on a beryllium-copper alloy. The proper selection of the etchant, indeed, is of the utmost importance when effort is directed to some specific structure in the specimen. Since the etching solution attacks one group of constituents and leaves the other or others unattacked, the micrographer should have a thorough knowledge of this phenomenon; and, above all, he should definitely know what structures he expects to see in the specimen under consideration so that he may conduct the etching accordingly. In other words, in order to reveal the full structure, every metallic material requires a specific etching solution. A list of etchants will be found in the Appendix of this book.

In an alloy containing more than one constituent, the etching is influenced by the difference of electrolytic potential that exists between the component structures subject to the action by the etching reagent. When the etching solution is in contact with the surface of the specimen, there will be formed an electrolytic cell with one of the constituents acting as an electro-positive element (anode) and the other or others collectively as the electro-negative element (cathode). The etching is usually confined to the former element, but as the reaction progresses the cathode constituent begins to become affected, which condition may not be desirable for true structural investigation of the metal. Therefore,

all etching solutions are allowed to act on the metal considered for a predetermined interval of time, so that the cathode in general may remain unaffected and appear possibly in relief. Since the action of the etchant is directed to the anode, this constituent becomes roughened and appears dark or may take on various spectral colors when viewed under the microscope with an illumination filtered to approximate daylight. These colors are characteristic with many metal constituents, and at times become an index in the identification of the various constituent structures.

The etching procedure embodies the thorough cleansing of the polished surface to be etched, the use of a proper type of etchant for a specific interval of time, and at a definite temperature. Emphasis cannot be too strongly born on these four factors, because as a result of negligence to observe any one factor, the unnecessary repetition of the entire process from repolishing to final etching may have to be accrued. It is, therefore, urged that the directions given for each reagent serving a specific purpose should be adhered to very closely.

The specimen to be etched is first cleansed thoroughly by washing its surface with distilled water followed by a careful swabbing with ethyl alcohol (98% grain alcohol). This step removes any film of grease or oil that may be adhering to the surface of the specimen from previous lapping with an abrasive wetted with oil. The specimen is then thoroughly dried and treated with the etching reagent either by immersing it into the solution or swabbing it gently with a tuft of soft cotton saturated with the reagent. In either case, as the etching progresses, the polished surface will gradually become dull, and for one having some experience in the art it will be an easy matter to determine when to arrest the etching.

With some types of etching procedures, the reagent is heated to a predetermined temperature which is sustained throughout the etching interval. If the direction calls for the immersion of the specimen, the latter is suspended by means of forceps in the reagent contained in a small beaker or in a pyrex watch-glass with the tip of a mercury thermometer immersed into the solution. The specimen is agitated in the etchant while it is being treated to remove all bubbles that may have been formed as a result of the chemical reaction of the etching fluid on the specimen.

When the proper etching has been accomplished, the specimen is immersed into a large beaker of cold distilled water and vigorously agitated to wash off the chemical reagent. The specimen, then, is washed with ethyl alcohol and dried by blowing on it with a blast of warm air. It is now ready for examination under the microscope.

The polishing and etching of the specimen may also be achieved by an electrolytic process, in which a weak current varying from

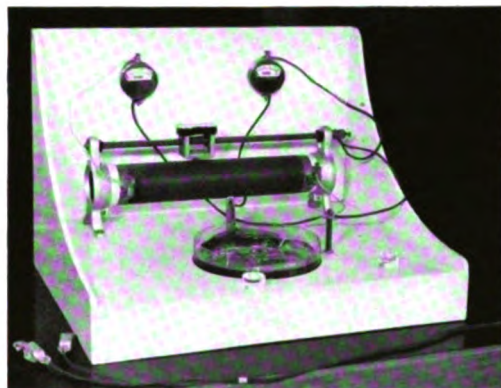


Fig. 148. An Electrolytic Etching Apparatus Improvised by the Author and in Use With Success in His Laboratory.

0.1 to 2.0 amperes per square inch of the anode surface is passed through a suitable electrolyte in which the specimen acts as the anode, and a rod or plate of graphite is made the cathode. The two electrodes are placed in the electrolyte preferably parallel to each other and from $1/4$ to 3 inches apart. The current is furnished from a storage battery or from a direct-current generator. A rheostat, placed in series with the specimen, regulates the current and the voltage to be used in the electrolytic process, in which the voltage rather than the current appears to be the controlling factor.

In a comprehensive article on "The Electrolytic Polishing of Brass and Copper," *Metal Progress*, July 1942, Page 77, G. J. Foss, Jr. and Larry Shiller describe an electrolytic polishing and etching process in which the electrolyte is 25 to 55 per cent commercial orthophosphoric acid. The specimen to be treated is made

the anode and is placed in the bath in a horizontal position with the cathode having 10 times the surface area and arranged in a vertical position. A voltage value varying from 0.7 to 2.0 volts with a preferable average of 1.1 volts for moderate speed work is used, the time of polishing lasting from 10 to 15 minutes.

In the same article the authors make reference to an electrolytic etching procedure described by G. C. Williams and G. Rieger, in *The Metal Industry*, May 24, 1940, Page 461. The specimen to be etched is made, as usual, the anode immersed in an electrolyte consisting of 10 Cc of 1/10th molar ammonium acetate, 30 Cc of 0.14 molar ammonium hydroxide, 30 Cc of 0.50 molar sodium thiosulphate, and 30 Cc of distilled water. A current density of 2 amperes per square inch is employed.

Electrolytic etching is particularly useful in the etching of cold-worked metals, alloys that are heat or corrosion resistant and cannot be conveniently etched by the usual methods. A number of electrolytes, such as dilute acids, or dilute alkaline solutions, may be successfully employed in the etching of various metals especially those that require a high degree of accuracy in revealing the microstructure together with freedom from blemishes of any character. Some of the most prevalent and satisfactory electrolytic reagents with directions for use will be found in the Appendix.

4. Procedure for Photomicrographing the Specimen.—It is customary to study the specimen immediately after it is etched, as chemical reaction of the atmospheric gases upon the metal may oxidize its surface, thus obscuring the visibility of the structures under investigation. If it is desired to preserve the specimen for some time before a study is made, its surface may be smeared with cedar oil or paraffin oil. A still better method is to keep the specimen in vacuum, or, in a suitable desiccator containing medium size crystals of silica gel in abundance. The usual practice, however, favors studying the specimen as soon as it is prepared and subsequently photographing it under a suitable magnification for further reference.

Wherever a microscope is employed, photomicrography may be applied to advantage, as it supplements visual observation and permits the clarification of research findings through comparison of photographs of several specimens or of the same specimen

both before and after it is subjected to special treatments such as thermal treatment, recrystallization, or heat tinting. With a modern photomicrographic equipment, the procedure has become comparatively simple. The operation, however, requires an elementary knowledge of the principles of photography, aside from skill in the art of proper selection of the specimen and its preparation.

A. APPARATUS USED AND PROPER ILLUMINATION.—A photomicrographic apparatus, also known as a metalloscope, essentially consists of a microscope, a suitable illuminant, a camera, and accessories such as to be described presently. A modern metalloscope of the ultimate magnitude is shown in Plate XII, and the reproduction in Plate XIII illustrates by reference to numerals the various parts of the inverted microscope structure which is illuminated by a motor-driven mercury arc lamp. The apparatus affords a range of magnification from 26x to 2000x and higher, with minimum of effort in the manipulation of its different parts and in bringing the image to a focus. Its accessories include liquid cell, filter holder, iris diaphragm, and decentering diaphragm for oblique illumination.

In reviewing the various useful features required of a microscope, consideration should be directed to its objectives, which should be optically corrected, to oculars, and condensers, its permanency of alignment, rigidity with which the camera is supported, and, the least unimportant of all, to provision of means for eliminating the heat from the materials of the apparatus so that no change in the focus due to expansion of these parts occurs during the exposure. Vibration of any character from any source should be rigorously condemned, as a slight displacement of either the specimen or the objective may cause a large relative lateral movement of the image even to throw it out of focus under a high magnification. All these specifications have been complied with in the apparatus shown in Plate XII.

The body of the metalloscope illustrated in Plate XII is made of casting in which is mounted a stellite mirror that reflects the image received from the objective toward the photographic plate, which may be either a cut-film or a pack-film. A vertical illuminator is mounted over the stellite mirror, and the whole assembly, including the body, mirror, eyepiece, and the vertical illuminant, is mounted on a rigid table support. A rack and a pinion mechanism

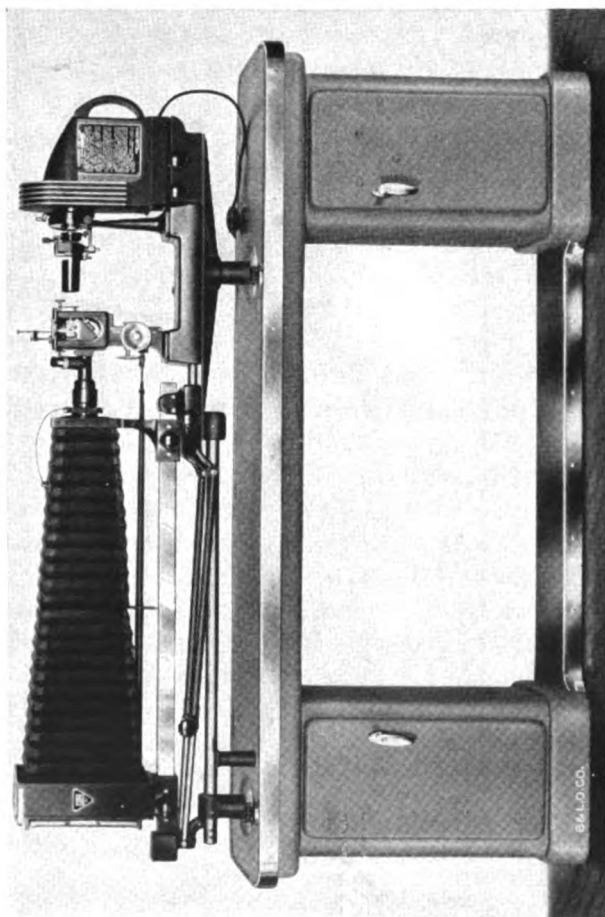


Plate XII.
Bausch & Lomb Metalloscope with Motor Driven Arc Lamp.

permit the vertical movement of the stage without tendency to produce lateral movement or vibration. By this arrangement, exposures of any length even with the highest magnification may be secured without any detectable unsharpness due to movement.

In order to reduce the weight to a minimum on the fine adjustment, the latter is made to carry only the objective, thus minimizing the strain on it and preventing the microscope from slipping out of focus during exposures. The coarse adjustment, on which the stage casting moves, is quickly and conveniently brought to proper setting without first looking at the position of the objective, as would be the case with an ordinary microscope.

The character of the illuminant is one of the determining factors in the securing of a satisfactory photographic image which will embody all the requirements of an interpretable photomicrograph. A perfectly polished and etched specimen may not present the information necessary in arriving at a conclusion regarding the condition of the constituents or the structural aspect of the specimen if inadequate illumination has been employed in the investigation. Four types of illuminations will be described here: They are, (a) *Oblique Illumination*, (b) *Vertical Illumination*, (c) *Dark-Field Illumination*, and (d) *Critical Illumination*.

(a) *Oblique Illumination*.—When there is little contrast existent between the structural components of the specimen under investigation, oblique illumination becomes of special importance. Such an illumination may be effected by directing a source of light onto the surface of the object at an acute angle (an angle less than 90 degrees). Since the light striking the specimen is reflected with the same angle as that of incidence, and consequently no light passes into the objective from this source, the surface irregularities consisting of the different component structures will appear in relief. The grains in general will stand out as black regions surrounded by lighter boundary lines. The illumination is excellent in lending itself to revealing pits and cracks in a polished, or etched, surface, as illustrated in Fig. 149.

Oblique illumination may be obtained from daylight by moving the microscope toward the window indirectly illuminated by sunlight. In an alternative case, an artificial light from a tungsten filament lamp filtered to daylight color may be focused onto the specimen by means of a lens having an adjustable aperture. The

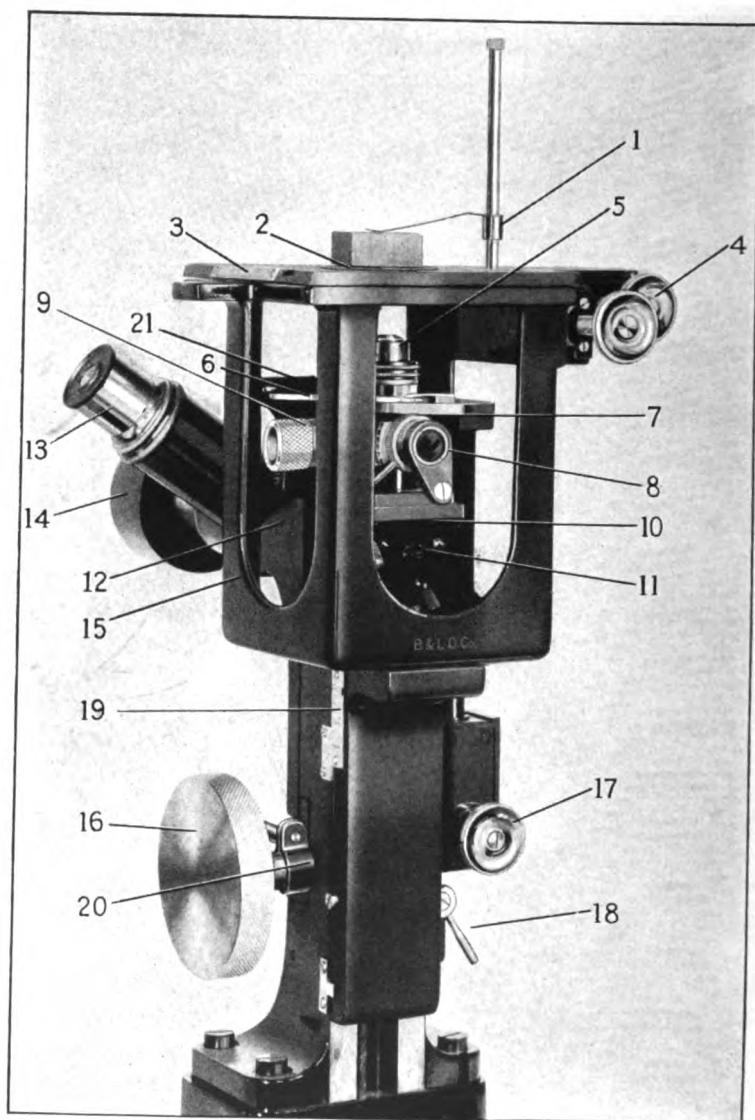


Plate XIII. Key to the Parts of the Microscope.

- | | |
|--------------------------------------|-----------------------------|
| 1. Specimen Holder | 11. Heat Shield Socket |
| 2. Stage Aperture Plate | 12. Microscope Body |
| 3. Mechanical Stage Scale | 13. Observation Eyepiece |
| 4. Mechanical Stage Adjustment Heads | 14. Camera Connector |
| 5. Objective | 15. Stage Casting |
| 6. Objective Handle | 16. Coarse Adjustment Head |
| 7. Iris Diaphragm Adjusting Ring | 17. Fine Adjustment Head |
| 8. Filter Mount | 18. Reducing Gear Lever |
| 9. Vertical Illuminator Mirror Mount | 19. Coarse Adjustment Scale |
| 10. Stellite Mirror Housing | 20. Coarse Adjustment Lock |
| | 21. Stabilizer |

method is depicted in the illustration shown in Fig. 150. An additional advantage of such an illumination is that the light may be focused onto the object from any angle to give the most desirable relief or contrast view of the field under investigation.

(b) *Vertical Illumination*.—Vertical illumination presents universal usage in work done with a metallurgical microscope. In this type of illumination, the beam of light is directed from a side tube at right angles to the optic axis and is made to fall on

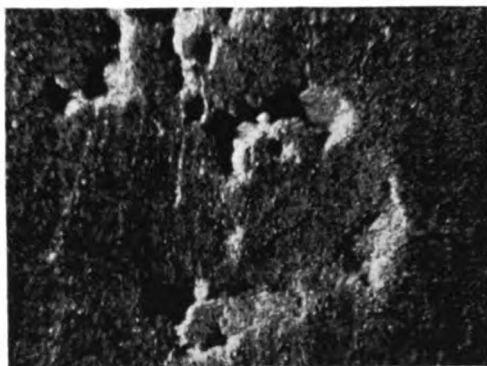


Fig. 149. Micrograph of Aluminum Alloy 356, Revealing Grains of Silicon, and a Large Number of Gas Holes and Shrink Pits.

either a reflecting prism or a plane glass reflector mounted at a 45-degree angle with respect to the incident beam. The light is reflected from this reflector through the objective onto the surface of the specimen and back to the ocular. Thus, the objective serves a dual purpose by acting as a condenser and as an image-forming lens. The general appearance of the image as regards the brightness of the structure is the reverse of that produced by means of the oblique illuminator in that the field appears bright with the included image dark.

Of the two reflectors, for greater amount of contrast and brilliancy of the image, the prism type at magnifications below 100x gives excellent results. But, since the prism reduces the effective aperture of the objective to one-half, the resolving power of the objective accordingly decreases. Therefore, for relatively higher magnifications, the use of plane glass reflector is preferred.



Fig. 150. Bausch & Lomb Metalloscope, Showing the Adjustable Illuminator with Filter.

Though the latter has a tendency to produce glare due to the dispersion of some of the light having reflected to the walls of the microscope tube and thereby having been absorbed, the defect can be minimized by proper adjustment of the illuminating beam in

conjunction with proper selection of the objective. This type of reflector should always be used in photomicrographic work at especially high magnifications, since the resolution is not impaired by slight loss of contrast. For both visual examination and photographic work the plane glass reflector meets with popular preference.

In either case, whether a total-reflecting prism or a plane glass



Fig. 151. Bausch & Lomb Model CM Metallurgical Microscope.

is employed, accurate adjustment of the incoming beam should be made in order that satisfactory results may be derived from vertical illumination. That is, in order to obtain an evenly distributed illumination on the specimen, the light spot that forms on the back side of the objective in the field of view should be, of consequence, centered to the field by accurate alignment of the reflector with respect to the objective and the incident beam.

(c) *Dark-Field Illumination*.—Unlike the bright-field illumination, in which the objective serves both as a condenser and as

an image-forming lens and produces a dark image against a bright ground, the dark-field illumination forms a bright image in a dark field. The light beam is projected through the usual side tube mounted at a position normal to the optic axis of the microscope on a thinly-silvered prism which reflects it onto a concave spherical mirror. From this mirror, the rays are again reflected onto the surface of the specimen converging to a small area at a great obliquity. Since this arrangement ensures a higher numerical aperture, extreme contrast together with high resolving power may be obtained from this type of illumination.

In the model CM metallurgical microscope illustrated in Fig. 151, the side tube contains a slot for various color filters, or polarizing plates such as Polaroid polarizer, the condenser lens, and the field and aperture diaphragms, thus permitting a complete control of the incident illumination. The tubular mount is fitted with both plane glass and prism reflectors, the latter serving the purpose of securing oblique illumination where necessary.

B. MAGNIFICATION, AND RESOLUTION.—As we have already noted, a microscope comprises in principle an *objective*, a *tube body*, and an *ocular* which is also called the *eye-piece*. If the objective has a magnifying power of, for instance, 4.4 and the magnifying power of the ocular is given as 10, the magnification of the combination will be $4.4 \times 10 = 44x$. The magnifying power of every microscopic lens is usually marked on the side of the cylinder in which it is mounted. By various combinations of the ocular and the objective, magnifications ranging from 5 to 2500 ordinarily, and over with special equipment, may be secured.

An equation expressing linear magnification in visual examination for a tube of 160-mm in length and objectives having focal lengths up to 25 millimeters may be given by the following formula:

$$M = \frac{Ln}{f} \quad (122)$$

where, M is the linear magnifying power for visual examination, L is the length in mms of the microscope tube measured from the ocular to the objective mount, f is the focal length of the objective, and n is the magnifying power of the ocular or the eye-piece.

For photographic magnification of an image which is projected on the photographic plate or film mounted in the metalloscope, an expression giving the approximate quantitative value of this quantity may be given as

$$M = \frac{dm}{250} \quad (123)$$

in which, M is the photographic magnification of the image, d is the distance of the projection in millimeters, and m is the product of the magnifying powers of the ocular and the objective at a projection distance of 250 millimeters. (Note: By "projection distance" is meant that for most practical purposes the apparent image is formed at a distance of 250 mms from the eye when a tube length of 160 mms is taken as standard.)

For instance, if the magnifying powers of the ocular and the objective are respectively 8 and 10, find the magnification of the image at a projection distance of 375 millimeters. According to equation (123), m is equal to $8 \times 10 = 80$, and the magnification will be $80 \times 375/250 = 120$.

In the formation of a microscopic image, the degree of resolution rather than the amount of light passing through the objective is of prime importance. The sharpness of the image and the resolution of the structural detail are dependent on the maximum angle of the cone of light entering the objective from the light focus at the surface of the specimen. This angle formed by the marginal rays of the incoming light cone with its base at the objective and its apex on or beneath the surface of the specimen is known as the *angular aperture*.

The intensity of light constituted by the number of light rays passing through the objective is dependent upon the angular aperture and on the *index of refraction* (light-bending property) of the medium included between the specimen and the objective. If this medium is air, there will be a smaller number of rays admitted into the objective, whereas if a liquid of high refractive index is substituted for air, the rays reflecting from the surface of the object will be refracted (bent) toward the optical axis, thus admitting a greater number of reflection rays from the objective surface. The effect becomes more significant for especially high power magnification. This is precisely the reason why magnifica-

tions above 800 are generally accomplished under an oil-immersion lens. Cedar oil is usually employed as immersion fluid because of its high index of refraction.

Abbe has formulated a quantitative expression for the relative performance of an objective, used dry or oil-immersed, on the basis of the angular aperture and of the index of refraction of the intervening medium, and he has designated the value of this as *numerical aperture* (written *N.A.*) of the objective. This fundamental principle may be further explained by stating that the numerical aperture of an objective is numerically equal to the product of one-half the sine of the angular aperture and the index of refraction of the medium between the front lens and the surface of the specimen. Written in an equation form, we have

$$N.A. = n \sin \Theta \quad (124)$$

where, n is the index of refraction of the medium, and Θ is the angle between the marginal ray and the optic axis of the microscope, i.e., Θ is one-half of the total angular aperture of the objective.

It will be noted here that the limiting angle is 90 degrees, the sine of which is 1.00. For air, the value of n is 1, whereas for cedar oil it is 1.50. Therefore, it will be obvious that for a high power magnification the front lens will, of necessity, have to be brought nearer to the object, and the angle subtended will be large but never above 90°.

Let us consider an angle of 90° short of an infinitesimal fraction of one degree, and let us further assume that the intervening space is occupied first by air of refractive index 1.0 and then by cedar oil of an index 1.50. Consequently, the value of *N.A.* will be 1.5, and the light admitted into the objective will be increased by the square of this quantity. Using the same objective but doubling the magnifying power by changing the ocular, the light intensity will become one-fourth. Thus, if it is desired to increase the magnification without sacrifice in intensity of the light admitted, the *N.A.* should be increased in direct proportion. That is, by doubling the magnifying power the intensity will reduce to one-fourth, and at the same time by doubling the *N.A.* the original intensity will become four times as great. Hence,

there will be no change in the intensity of the light forming the image.

The above discussion, then, leads to another factor of great importance—the *resolution* of the image. The ability of an objective to produce sharply defined image detail which at lower magnifications cannot be distinguished is fundamentally expressed as its *resolving power*, which increases in direct ratio with the value of the numerical aperture and also with the wavelength of the light illuminating the specimen under consideration. This relation may be further elucidated by saying that if a certain lens will resolve a maximum of 1500 lines per centimeter so that each line will appear under the microscope as distinct and isolated from others, a lens having an *N.A.* twice the value of that of the first will resolve 3000 lines, and one having five times as large an *N.A.* will resolve 7500 lines per centimeter.

The relationship of the resolution of an objective to the numerical aperture and the wavelength of the light used to illuminate the object may be given in an equation form as

$$R = \frac{\lambda}{2N.A.} \quad (125)$$

in which, R is the distance between two points resolved in the specimen, and λ is the wavelength of the incident illumination. This formula will only apply to a condition of illumination where the pencil of light focus is equal to the aperture of the objective. It will be further observed that the *shorter the wavelength* of the illuminating cone of light the *greater the resolution*. Hence, an illumination filtered to give a greater amount of green and blue spectral rays is indicated for high power magnification work.

C. PHOTOGRAPHIC TECHNIQUE, AND EXPOSURE.—The photographic procedure is comparatively a simple one. The specimen to be photographed (also termed micrographed) is placed under the objective, in the case of an ordinary table microscope, such as shown in Figs. 150 and 151, and a suitable camera minus its objective is mounted over the ocular of the microscope. The illumination is turned on, and when the image at the object is focused on the ground glass of the camera, the glass is taken out from the slot and a pack of cut-films or a loaded double-plate holder is inserted. A series of test exposures consisting of

1/2 second, 1 second, 2, 3, 4, 6, and 8 seconds are made on a single plate by moving the opaque cover on the plate holder a predetermined distance equivalent to a unit fraction of the number of trial exposures to be made on the plate. When the plate is developed, the correct exposure time may be determined by the time required to produce the best image density in any one strip of the trial exposures.

To illustrate the above procedure, let it be assumed that the photographic plate dimension is 2-1/2 x 3-1/2 inches. The cover plate of the exposure holder may be divided along its 3-1/2-inch length into, for instance, seven equal strips, each measuring 1/2-inch in width, by drawing ruled lines. The first exposure is made on the whole plate with 1/2-second, and the cover plate is pushed in 1/2-inch. The second exposure is made with another 1/2-second, and the cover plate is again pushed in a distance of 1/2-inch. The succeeding exposures are made with exposures of 1 second, 1 second, 1 second, 2 seconds, and 2 seconds, after each exposure the cover plate being moved 1/2-inch along a closing direction. The exposure on each strip, then, will be, starting from the first to the seventh, 1/2 second, 1 second, 2 seconds, 3 seconds, 4 seconds, 6 seconds, and 8 seconds for the last exposure, computed on the basis of the above-given exposure intervals.

When the photographic film is treated in the processing solutions (developer, and the fixer), the correct time of exposure may be determined by visual examination of the film and taking the exposure required to produce the desired density as the correct exposure time. This procedure, however, is not necessarily carried out every time a new specimen is photomicrographed. The metallographer will soon acquire the proper skill, and by use of some discretion he will be able to determine the exposure time by merely viewing the microscopic field under interest.

In photographing with large stationary metallosopes, such as the one shown in Plate XII, the specimen is held firmly above the objective and the microscopic field is scanned through the observation eyepiece (No. 13, Plate XIII) for the desired region to be photographed. The image is brought into focus on the ground glass at the end of the bellows extension. The glass is then replaced by the photographic plate and the exposure is made by a permanently mounted automatic shutter.

As has been stated previously, the degree of resolution is directly dependent upon the numerical aperture and on the wavelength of the illuminating source of light. By using apochromatic lenses, the range of suitable wavelengths to effect optimum resolution is 3900 to 5100 angstroms. Wavelengths shorter than 3900 angstroms may be successfully used if the system of lenses are made of quartz, fluorite, or borosilicate, which respectively admit wavelengths (ultra-violet) as low as 1500, 1250, and 3000 angstroms. Ordinary optical glass absorbs practically all ultra-violet wavelengths below 3000 angstroms, not including that part of the wavelengths which are superimposed on the long-wave x-radiations. A suitable light source for this type of illumination (ultra-violet illumination) is a filtered carbon-arc lamp or a mercury-vapor discharge lamp, either one of which is generally furnished on large metalloscopes as standard equipment.

5. Interpretation of Microstructures.—To go about for setting up rules and directions for interpreting microstructures that may appear in various shades, forms, and sizes, somewhat dependent on the etchant employed, and largely a function of the structural constituents of the specimen considered, will appear at first sight to be nothing short of folly. However, we may direct our attention specifically to constitutional appearance resident and fundamentally common to all microscopic structures, namely the crystalline states in pure metals and both crystalline and eutectic constituents in alloy structures. Contributory to this information derived through visual examination of the structures in the microscopic field, if other data consisting of constitutional diagrams, results from a qualitative chemical analysis, or a quantitative spectrographic or x-ray diffraction patterns, be supplemented, a reasonable estimate of the chemical composition can be secured. This will establish a criterion on which further study of the microstructure may be based in the light of constitutional diagnosis.

It may be said, in passing, that in the absence of exact knowledge as regards the constitutional aspect of the microstructure, it will be deemed futile to make an attempt to interpret microstructures revealed in the microscopic field. But, generally data on the composition of the metal to be micrographed are available in the metallurgical tables or in special literature furnished by

the manufacturer of the material. In such instances, the microscopist should have little or no trouble in distinguishing the various microconstituents of which the metal under examination is composed.

It is to be remembered, indeed, that any attempt of such an interpretation involves previous and specialized training which is intensive as well as extensive. However, we may bring out one important point which is the polyhedral dimension of every crystalline structure and its boundary lines in the case of pure metals, and the crystalline and the intercrystalline constituents in alloys, which characterize the material and can be detected by any one having an elementary knowledge of the use of a microscope. Consequently, since excellent textbooks on the subject are available, and some of which are listed at the end of this writing under reference column, and, further, in order to be able to convey an authentic information in a detailed discussion will require space outside the scope of this writing, the author takes the liberty of abstaining from immersing further into the subject, which, in his opinion, is better learned by actual visualization of the various microstructures and by practical instruction by one highly specialized in the science, rather than by knowledge acquired through books or other publications.

6. Analysis of Metal Surfaces by Electrographic Method.

—It has been slightly over a decade since the first successful application of electrographic method to the qualitative analysis of the surfaces of metal specimens, but the impetus to the further development of the method had not been given until 1938 or 1939. Within the last few years, then, considerable light has been thrown on the fundamental nature of the electrochemical reaction between the electrolytic mediums intervening the successful determination of the elements particularly when they are diffused in a solid solution in an alloy. Therefore, the nature of the task has been not only extensive but a difficult one, and at times the results have been discouraging owing to the difficulties in selecting an appropriate medium which will bring about a certain desired reaction with one group of elements and at the same time will discriminate others.

The electrographic method of identifying various elements found in a given metal specimen consists of polishing the surface

of the specimen under consideration (to the same degree as in macrographic work), dissolving a thin layer of the surface in an appropriate electrolyte under the influence of an electric current, depositing this layer of the metal in a suitable material such as paper or other porous material, and subsequently developing the paper in a proper reagent for the detection and identification of the elements by the color they produce on the paper. By this method, identification of various alloys and inclusions, qualitative determination of elements, and detection of porosity in various metal coatings have been possible. The scheme is not only simple but also affords a rapid and non-destructive analysis when conducted under adequately controlled conditions.

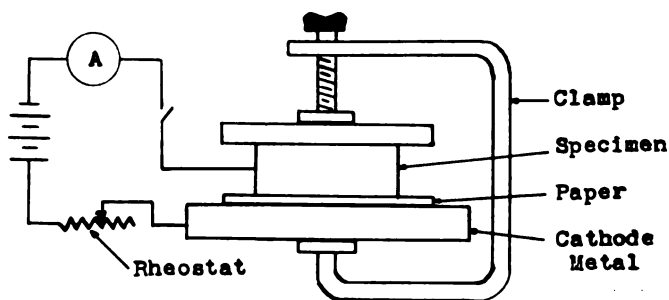


Fig. 152. The Schematic Diagram of the Electrographic Circuit.

In practice, the surface of the specimen to be treated is polished and placed in contact with a gelatin-coated paper (of the order of Eastman Inhibition Paper) saturated with an aqueous solution (3 to 5%) of a neutral salt such as Rochelle salts, potassium nitrate, potassium sulphate or sodium nitrate. A block of aluminum or magnesium is placed against the reverse side of the paper, and the assembly is pressed together by means of a suitable clamp producing an evenly distributed pressure between the two interacting surfaces.

A source of direct current such as furnished by a storage battery or by dry cells is used. The positive terminal of the battery is connected to the specimen and the negative terminal is connected through an ammeter to the aluminum or magnesium block forming the cathode of the circuit. Thus, the specimen becomes the anode of this tiny electrolytic cell.

Depending on the area of contact of the specimen, the current varies from 0.1 to 1.5 amperes for usual small specimens, the current density remaining about 2.5 amperes per square decimeter. The electrolytic interval is prolonged from 20 seconds to 50 seconds depending on the sensitivity of the electrolytic reagent used.

To bring out the colors corresponding to various elements present in the specimen, the gelatinous surface of the electrographic paper is treated in a developing bath. For instance, for the identification of copper, the paper is developed in an alcoholic solution of ammoniacal benzoinoxime, and a green color obtained on the paper is an indication of the presence of copper. For the identification of iron, potassium ferrocyanide is used, which renders the paper a characteristic blue color. For silver, a potassium chromate bath may be used to give a brick-red color, whereas a dimethylglyoxime developer for the identification of nickel will produce a scarlet-red color on the paper. An aqueous solution of potassium iodide will develop an orange color with bismuth as the element under investigation. It should then be noted that the developing reagents in general correspond to those used in the qualitative analysis of these metals.

Though the sensitivity of the test is a function of the amount of the unknown metallic element present, on the character of the electrolyte, and on the intervening elements, the extension of the scheme, by further study in this direction, to the development of a method whereby quantitative analysis of the metal under investigation may be performed appears to be entirely feasible.

CHAPTER XI

IMPORTANT AIRCRAFT MATERIALS

1. Aluminum and Its Alloys.—Aluminum stands, at present, as one of the topmost among the commercial metals in tonnage consumed. It occurs principally as silicates in clays and in feldspar, and is chiefly derived from bauxite, an impure hydrated oxide of aluminum having the chemical formula $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ and $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, in association with extraneous compounds characterized by iron oxide, sand (silicon dioxide), and titanium oxide. The chief sources of bauxite are in the United States, British Guiana, and a few other European countries.

Prior to the extraction of the metallic aluminum from bauxite, the latter is first converted into alumina free from all impurities. Bauxite yields between 60 to 65 per cent pure alumina, which, in turn, yields about 38 per cent pure metallic aluminum. In production, alumina is dissolved in molten cryolite, and by electrolysis at 1000°C . the metal is separated in the molten form and deposited at the bottom of the electrolytic cell, from which it is removed from time to time. The electrolytic process of this metal was discovered by Charles M. Hall in America over fifty years ago. The method has been so improved subsequently that at present the reduction process yields aluminum of a purity between 99.8 to as high as 99.99 per cent, dependent on the facilities available and on the manufacturer's skill.

Aluminum is a white metal resembling tin or zinc in appearance. One of its outstanding qualities is its lightness, which makes it most useful especially in the aircraft industry. It is about one-third as light as steel, brass, or cast-iron, and stands second in malleability and sixth in ductility among commercial metals. While it possesses high resistance to the corrosive action of the atmosphere and various chemical compounds, in contact with many metals it rapidly corrodes because of its strongly electropositive nature. It is this last characteristic of aluminum and its alloys that makes an aluminum casting susceptible to rejection when metal segregation or certain metallic inclusions are indicated in the radiograph. Aluminum further possesses the property of high

reflectivity of all visible, ultra-violet, and infra-red, wavelengths, has moderate high thermal and electrical conductivity, can be fabricated in various textures and colors, and is weldable by all prevalent commercial methods.

Commercially pure aluminum has a tensile strength of about one-fourth that of steel. But, this can be markedly increased by cold-working the metal or by alloying it with other metals. The principal elements which are employed to form the alloy are copper, silicon, magnesium, zinc, manganese, nickel, and iron. Chromium, lead, and bismuth are also used in small amounts as alloying elements. Some of these form "*strong alloys*" through appropriate thermal treatment, as a result of which the metal influences its use for greater variety of fields of application. Through adequate selection and compounding of the alloying elements in combination with proper heat treatment, a series of aluminum alloys have been produced comparable in many respects to structural steel.

Among numerous applications of aluminum in industry is its use in commercial food-processing. Culinary equipment such as cookers, tanks, kettles, pipes, screens, vacuum evaporators, and a number of other kitchen utensils are made of aluminum. In the dairies, the extensive use of aluminum is characterized by automatic pasteurizers, heat exchangers, storage and truck tanks, piping, valves, milk-bottle hoods, cheese vats, etc. In the brewery, the metal appears in the form of coolers, kettles, tanks, fermenters, beer barrels, dippers, buckets, skimmers, etc., because of its lightness and freedom from corrosive attack by chemical substances involved in this field.

In the production and packaging of fruit juices, preserves, and other foodstuff, aluminum is the chief metal that goes into the making of the equipment that produces these products. Aluminum is also used for the caps and seals of bottles containing edibles. Foils of the metal find wide use in the wrapping of photographic films, packaging of cheeses, candies, tobacco, and for decorating greeting cards.

Because of its high resistance to the corrosive attack by sewage fumes and gases, and because its corrosion products are colorless, aluminum finds diverse uses respectively in plants of sewage disposal and in textile and paper manufacturing industries.

In rubber industry, from the collection of raw latex, its shipment, and coagulation to the process of vulcanizing and curing, aluminum equipment is almost exclusively used in view of its lightness, resistance to attack by sulphur or its derivatives employed in rubber, and consequent advantages offered by its high heat conductivity and ease of handling.

One of the unique properties of aluminum which is not met with most other metals is its non-sparking characteristic, which quality makes it of avail in the storage and shipment of nitroglycerin, important electric circuit wirings especially when they are bare, x-ray aërials, machines for packing dynamite, equipment used in petroleum industry, and in machinery used in the handling and processing paints, varnishes, aldehydes, alcohols, and in general in the manufacture of a wide variety of organic and inorganic chemicals. Aluminum, indeed, appears to be one of the most popular metals, if not the only one, of important industries in the world.

Since the writing of this text is principally concerned with the production and inspection of materials of common industrial use, especially those employed in aircraft and automotive industries, where the use of cast aluminum parts has superseded those of forgings, rollings, etc., because of the low cost and more rapid production of cast products, we shall direct our attention in general to aluminum castings of aircraft structures, and the methods and processes involved in the production of materials of this character. However, it will be almost impossible to present here a complete account embodying the production, use, and application of all types of aluminum castings. We shall, therefore, survey only those aspects of the subject that appear more common and most practical from the standpoint of the reader.

(a) *General Principles Involved in Casting Aluminum.*—Casting aluminum products of commerce is not only an art in itself but requires some measure of skill acquired through a combination of empirical practice and theoretical methods. With present urgent demand for a great variety of products of this metal, the field has become so specialized that in order to produce high quality castings it is very essential that a thorough grasp of the knowledge of the foundry characteristics of aluminum be acquired in establishing practices that will be effective in controlling the

foundry procedures that are varied and in some cases are complex. Much useful knowledge has been acquired, however, within the last few decades through research facilities of many technical laboratories in this country and which knowledge has been partially or wholly fused with empirical practice that many foundry variables now have been brought into close control of the founder, whereby the achievement of superior quality production has been made possible.

A close survey of foundry practice discloses that proper control of melting of the ingot is one of the most readily controlled yet most frequently overlooked variables. The intermediary operations between the melting and the pouring of the metal into the mold may cause an impairment in the final quality of the metal if inadequate control over the melting procedure without predetermined establishment of temperature has been exercised. To this respect mention is of consequence that the molten metallic aluminum has great affinity toward absorbing gases such as hydrogen, and oxygen. Since the tendency of these gases to combine with aluminum increases with increase of temperature, care should be exercised to avoid temperatures in excess of 1300°F. for direct-flame melting, and 1500°F. for indirect-flame or induction furnace melting.

In the case of oxide formation (referred to as dross in radiography), which may mix with the metal in the molten state, its separation from the base metal will be difficult owing to the densities of the metal and its oxide being very close. Hence, agitation of the molten aluminum should be omitted if practicably possible. In the presence of atmospheric moisture, an impervious film of aluminum oxide is usually formed on the surface of the solidified aluminum casting and which film serves to protect the metal against further attack by most gases and chemicals.

There are two types of furnaces in prevalent use—direct- and indirect-furnaces. The first type is generally fired with gas, fuel oil, or coke, whereas the latter is heated by electricity. The former two combustibles find extensive use because of their affording a more accurate temperature control, though they may not be as economical as coke. Induction furnaces are gradually finding increasing favor in the modern foundry because of the consistent,

dependable, and accurate results that are obtainable through their use.

It has been already discussed in a previous occasion that temperature plays a role of first importance in melting, casting, molding, and freezing procedures in the founding of a metal, especially of an alloy. The gas absorption characteristics of aluminum increases with increase of temperature of the molten metal, and hence an increase in the resultant oxidation occurs. It has been also pointed out that the maintenance of the molten metal at a high temperature has deleterious effect on the structure of the metal. A coarser and looser grain structure will result when aluminum is overheated, the rapidity of formation being a direct function of the high temperature at which the molten metal is sustained. Since aluminum does not indicate sharp color changes with change of temperature, properly calibrated millivoltmeters should be employed preferably in conjunction with automatic temperature-control devices.

In order to provide the metal or its alloy with proper physical and casting characteristics, special precautions should be taken to avoid contamination of the melt with extraneous elements or particles which will produce adverse effects on the founding of the metal. It is, therefore, desirable that various ingot metals or alloys be segregated and thorough cleansing of the equipment be ensured. In many foundries, a coating of whiting or Alorco Insulating Powder, manufactured by the Aluminum Company of America, should be used on all pots, pouring ladles, or other equipment which may be associated with the handling of the molten metal. As stated previously, agitation of the molten metal should be avoided to minimize the annoyance attributable to oxides and hence the resultant dross formation.

When melting aluminum-magnesium alloys, and in reclaiming skimmings and foundry scrap, fluxing treatments may be designed to eliminate oxide and deleterious gases. Materials commonly used as fluxes for the alloys of aluminum are aluminum chloride and zinc chloride which are transformed into a gaseous form at the temperature of the molten metal and tend to remove oxide formation and dissolved gases from the metal. In general, solid fluxes are used with the base metal at a temperature between 1350°F. to 1400°F. A gaseous flux such as chlorine, and liquid fluxes such

as a mixture of 50% sodium-silicofluoride with 50% sodium chloride, and a mixture of 70% cryoline with 30% potassium chloride, are also found to render satisfactory results in general practice.

The methods for making molds and cores for aluminum is same in general as for other metals. However, because of its light weight, molding of aluminum requires the adoption of certain specific practices quite unlike those effective for other metals. This property of aluminum and its alloys makes it unnecessary to construct heavy molds as for heavy metals, thus permitting a lower mold pressure and lighter sand ramming.

The mold material consists of *A.F.A.* classification 1G to 2G clay-bonded sand free from organic matter and tempered with 6% to 8% water and rammed lightly. The core for the casting is a combination of silica sand and a bonding material such as oil, dextrin, flour, resin, or pitch, the selection of the latter materials depending on the character of the molding process. The cores are so constructed that they withstand reasonable amount of handling yet are easily crushed by the casting during its solidification and consequent contraction.

Aluminum is very susceptible to hot shortness. Just below the solidification temperature, aluminum and its alloys possess very low strength so that any resistance to contraction during this transition period will result in shrinkage cracks. The effect is more prominent in aluminum-copper alloys having copper content above 5%, whereas with proper combination of silicon in aluminum to form aluminum-silicon alloys, the effect may entirely disappear, provided other conditions such as molding, gating, risering, and chilling are properly effected.

Proper application of suitable gating and risering practices will materially enhance the quality of the aluminum alloy castings. The gating should be so devised that in the solidification of the metal an adequate supply of the molten metal is ensured to the individual sections as they solidify. This can be accomplished by proper positioning of the gates and risers supplemented by chills embedded in the mold to control the solidification process especially of the heavier sections. Thus, the solidification may be made to start from a point remotest from the gated area and proceed toward the risers which provide with liquid metal any

deficiency of the molten metal due to shrinkage. Risers further serve in eliminating gases and oxides formed during the molding, and lend themselves to the reduction of the temperature gradient of the true casting in the mold.

Casting of aluminum requires multiple gating so that the molten metal may enter the mold cavity progressively at a uniform rate. With such an arrangement, the pouring temperature may be appreciably lowered, affording a lower temperature gradient. As a result, the sequence of solidification proceeds more favorably, and the tendency of the metal to result in shrinkage cracks is minimized. It may be also deemed desirable in some cases to cut the gates into the risers, preventing shrinkage within the metal frequently occurring near the gate entering the casting.

As it was discussed fully in Chapter VIII, the prevalent defects in metal castings are characterized by shrinkage cavities, dross inclusion, blowholes, cracks, porosity, etc. These imperfections may be eliminated to a large extent by the proper combination of alloying, molding, risering, and chilling practices. For instance, shrinkage cavities appearing in castings are largely due to improper feeding of the molten metal and its uneven solidification. Changing the gates and including suitable chills and risers to provide cooler metal in the sections embodying the defect will improve or even entirely eliminate the recurrence of the condition.

Failure to exercise care in handling the molten metal, by excessive agitation or by lack of skimming the oxide coating, will result in the inclusion of dross in the casting. If the above process is accompanied by rapid pouring, blowholes due to trapped air or to gases evolved from the wet mold will be formed. The defect is minimized by the inclusion of suitable gates and risers at proper sections of the mold.

Pin-hole porosity as a result of gases absorbed from the mold or during pouring process will be eliminated to a large extent by improved melting conditions, lower pouring temperature, and by adequate selection of the alloy combination. Lighter ramming of the mold, insertion of chilling blocks at appropriate sections, and proper feeding of the molten metal will aid in improving the condition.

Because cracks will occur due to the failure of the freezing metal to withstand the excessive resistance offered by the con-

traction in cooling, the sections in which such defects occur can be strengthened by means of ribs, or fillets as may be found desirable. Increased stresses in reduced areas produce foci of localized shrinkage which may often give rise to cracks. By obviating the cause of shrinkage, cracks will generally be precluded. High pouring temperatures resulting frequently in surface shrinkage will also be eliminated by proper provision of gating and chills in the mold.

(b) *Aluminum Alloy Castings*.—Only three principal types of alluminum alloy castings will be described here. They are: (1) *Sand casting*; (2) *Permanent-mold casting*; and, (3) *Pressure die-casting*. The first type employs sand as the mold structure, whereas the second and the third processes respectively use permanent metal molds, and dies in conjunction with metal molds.

As was stated in a preceding section, practically all aluminum castings are made of its alloys, owing to the higher mechanical properties and superior casting qualities that can be obtained from the alloy forms. The alloying elements commonly used are copper, silicon, magnesium, zinc, manganese, nickel, iron, and with some use of bismuth, chromium, and titanium. The improved characteristics of the alloy over the pure metal are developed around the proper combination of the alloy elements together with adequate heat treatment processes which further influence the strength and the hardness of the alloy. The alloys are designated by a number which may be preceded by a letter to indicate a variation in composition from the original alloy, or it may be followed by a symbol or the letter "T" and a number corresponding to a particular thermal treatment condition.

Of the cast alloys of aluminum, one of the earliest and most popular binary alloys is the one having copper content varying up to 15 per cent. The addition of copper up to 8 per cent to aluminum progressively increases the hardness and the tensile strength of the resulting alloy. With further addition of copper, the alloy becomes increasingly brittle so that comparatively fewer number of commercial applications would be permitted. Moreover, since aluminum-copper alloys are subject to intergranular corrosion, the alloy usually undergoes an appropriate thermal treatment prior to being put to service. Such an attack preferential to the grain boundaries renders the metal extremely sus-

ceptible to loss of ductility and tensile strength, and, with far advanced cases, the condition may even lead to complete disinte-

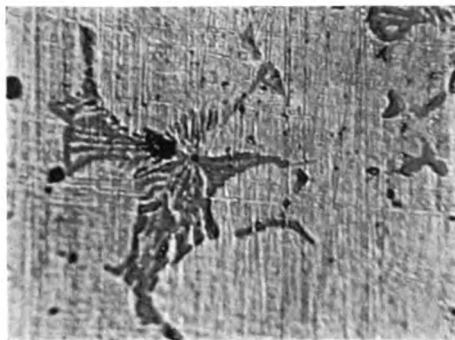


Fig. 153. Photomicrograph of Aluminum 195-T6, Showing CuAl_2 Constituent. Magnified. $\times 440$.

gration of the alloy constituents. Hence, most aluminum-copper alloys undergo proper heat treatment not only to off-set this corrosion-susceptible condition but also to eliminate internal residual

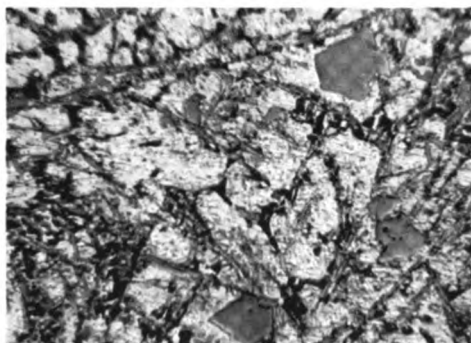
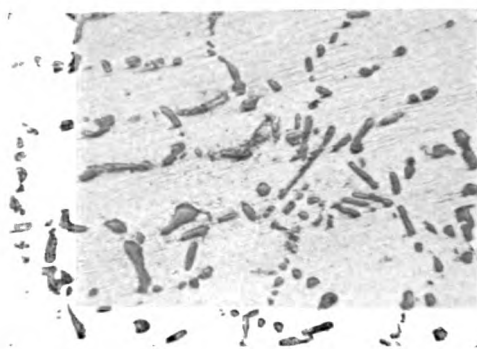


Fig. 154. Microstructure of Aluminum Alloy B195-T6, Showing Polyhedral Crystals of Silicon, and CuAl_2 Constituent of the Segregation Shown in Fig. 122a. Magnified. $\times 440$.

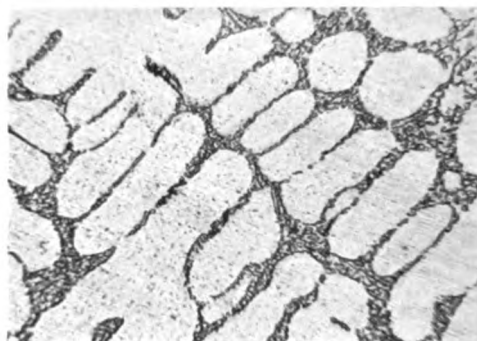
stresses, and to improve the inherent mechanical properties through crystal refinement and orientation of slip boundaries.

Of the binary aluminum alloys, the one designated as 195 contains 4 to 4.5 per cent copper, slight traces of impurities, and aluminum for the balance. The casting, when solution heat-treated

and aged at room temperature, is indicated as 195-T4, and is one of the most commonly used aluminum-copper alloys. When the casting is subjected to precipitation heat-treatment, after having been solution heat-treated, the designations 195-T6 and 195-T62



(a)



(b)

Fig. 155. Aluminum Alloy 356, (a) Grain Structure of the Un-Heat-Treated Specimen, and (b) Heat-Treated Condition of the Same Specimen. $\times 440$.

become in effect. These latter alloys have greater tensile strength and higher yield point than 195-T4, which, on aging at room temperature for a period of several months, acquires mechanical qualities comparable with those of the first two alloy tempers.

The alloy B195-T6, containing 4.5 per cent copper, 2.5 per cent silicon, 1 per cent impurity, and the balance of aluminum, has excellent permanent-mold casting qualities in addition to its resistive

property to corrosion. Its tensile strength approaches closely to that of 195-T6. The micrograph shown in Fig. 154 depicts the microstructure of the alloy.

Closely allied to the casting properties of the alloy B195-T6 is the aluminum-silicon alloy commonly known as 356. It is composed of 7.0 per cent silicon, 0.3 per cent magnesium, and aluminum for the balance. In the heat-treated state, the alloy is highly resistant to corrosion and possesses superior casting qualities to 195 but is less resistant to shock and impact loads than the latter. It is suitable for both sand casting and for permanent-mold casting. It is chiefly employed in the production of intricate castings consisting of varied gradations of thicknesses, and of hydraulic parts that offer leak-proof structures under conditions influenced by vacuum or pressure.

The mechanical properties of the alloy 356-T6 will be improved by the addition of a small amount of metallic sodium to the melt to sustain finer silicon particles throughout, to lower the eutectic temperature, and further to refine the size of the constituent grains. Rapid solidification of the metal will produce somewhat the same effect on the grain structure, tensile strength, and in the ductility of the alloy.

Another aluminum-silicon alloy of common commercial use is Alcoa alloy 43. It consists of 5 per cent silicon and 95 per cent aluminum. It is more ductile and resistant to impact loads than some types of aluminum-copper alloys but possesses somewhat inferior tensile and yield properties. The excellent casting qualities of the alloy permit its exclusive use for architectural and ornamental purposes. Because of its high resistance to salt-laden atmosphere, the alloy is ideal for use in the production of most marine castings.

In an attempt to improve the mechanical characteristics of the aluminum binary alloys, Alcoa No. 355, containing 5 per cent silicon, 1.25 per cent copper, and 0.5 per cent magnesium, has been developed. The alloy, in its heat-treated condition, combines the excellent casting properties of aluminum-silicon binary alloys with the superior mechanical qualities of aluminum-copper alloys. The alloy 355 and its modified composition A355, which latter contains nickel and manganese in addition, are especially suitable for liquid-cooled aircraft engines and for Diesel engines.

TABLE XIV:—NOMINAL COMPOSITION OF ALUMINUM SAND-CASTING ALLOYS.

Alloy	Percent of Alloying Elements—Aluminum and Impurities Constitute the Remainder.						
	Copper	Iron	Silicon	Zinc	Magne- sium	Nickel	Manga- nese
43	....	....	5.0	....	....	....	....
47	....	....	12.5	....	....	....	....
108	4.0	....	3.0	....	....	....	....
112	7.5	1.2	....	2.0	....	....	....
122	10.0	1.2	....	....	0.2	....	....
142	4.0	....	....	....	1.5	2.0	....
195	4.0	....	....	....	....	....	....
212	8.0	1.0	1.2	....	....	....	....
214	....	....	....	....	3.8	....	....
216	....	....	....	....	6.0	....	....
220	....	....	....	....	10.0	....	....
A334	3.0	....	4.0	....	0.3	....	....
355	1.3	....	5.0	....	0.5	....	....
A355	1.4	....	5.0	....	0.5	0.8	0.8
356	....	....	7.0	....	0.3	....	....
645	2.5	1.2	....	11.0	....	....	....

Heat treatment symbols are omitted because of their independence of the composition.

They are also used for crank cases, compressors, and cylinder heads. The former alloy can maintain its mechanical properties at operating temperatures approaching up to 400°F., whereas with A355 this temperature may be exceeded to some extent. Both of these alloys may be used for permanent molding without encountering any modification in their compositions as for sand castings. Due to rapid solidification of the casting in the metal mold, the alloy develops high tensile properties as that produced by thermal treatment. The improved metal structure when cast in a permanent mold further offers a high resistance to corrosion. The microstructure of alloy 355 is shown in Fig. 156.

Permanent-mold castings are of two types: (1) The type made in metal mold with metal cores, and (2) the semipermanent type which is cast in a metal mold having sand cores. The latter type of casting procedure offers the added advantage in that no limitations are imposed on the dimensions of the sand core which can be easily removed after the part is cast. The refinement of

the grain structure resulting from the rapid solidification of the casting renders the metal superior metallurgical properties. Permanent mold alloys are susceptible to thermal treatment for improvement of their granular structures and hence their physical characteristics. The heat treated alloy also possesses stability of dimensions against variation at high temperature operations.

For superior mechanical and chemical characteristics, aluminum-magnesium alloys stand even higher in rank than aluminum-

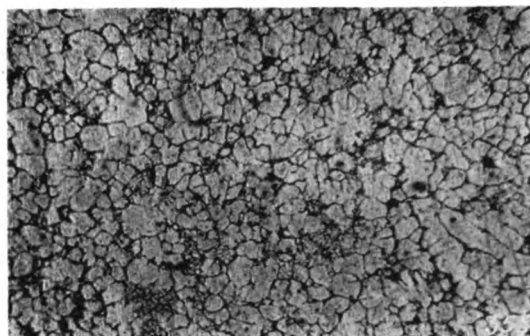


Fig. 156. The Microstructure of Aluminum Alloy 355. Magnified $\times 100$.

silicon alloys. An alloy of this class is Alcoa 220. It consists of 10.0 per cent magnesium and 90 per cent aluminum. It is the lightest of all the aluminum casting alloys but is capable of developing the highest tensile and yield strengths in addition to its superior properties of elongation and resistance to impact, tarnish, and to corrosion, when in the heat-treated condition (220-T4). It is used in the production of aircraft fittings, electric motor housing, draft gear parts, and in miscellaneous automotive castings where maximum strength and impact resistance are of prime considerations. The casting of the alloy requires special foundry technique, and it is difficult to cast from it intricate parts that are both leak-proof and are subject to radial pressure.

The aluminum-zinc binary combination, developed as one of the earliest alloys in industry, possesses satisfactory mechanical properties, but at room temperature it rapidly ages, losing a

TABLE XV:—NOMINAL COMPOSITION OF ALUMINUM
PERMANENT-MOLD CASTING ALLOYS.

Alloy	Percent of Alloy Elements—Aluminum and Normal Impurities Constitute the Remainder.					
	Copper	Iron	Silicon	Zinc	Magnesium	Nickel
43	...	...	5.0	...	...	...
A108	4.5	...	5.5	...	...	...
B113	7.0	1.2	1.7	...	...	...
C113	7.0	1.2	4.0	2.0	...	...
122	10.0	1.2	...	...	0.2	...
A132	0.8	0.8	12.0	...	1.0	2.5
138	10.0	1.4	4.0	...	0.2	...
142	4.0	...	...	...	1.5	2.0
B195	4.5	...	2.5	...	...	...
A214	...	...	...	1.8	3.8	...
355	1.3	...	5.0	...	0.5	...
356	...	...	7.0	...	0.3	...

Heat treatment symbols are omitted because of their independence of the composition.

substantial magnitude of its ductility and corrosion resistance. Aluminum-zinc alloys at present find practically no commercial use. A ternary alloy, designated as 645, consisting of 2.5 per cent copper, 1.25 per cent iron, and 11.0 per cent zinc, provides a metal with characteristics intermediate to aluminum-copper and aluminum-silicon alloys. It possesses reasonably high tensile strength and high ductility, the latter property gradually being reduced by aging at room temperature.

Another type of casting process which has become known as die-casting differs from other types of castings in that the molten metal is forced, by a hydrostatic pressure ranging from 400 to 500 pounds per square inch, into a metal mold or die and is retained until solidification is complete. A somewhat modified process employing between 2,000 to 250,000 pounds per square inch is used for bronzes, beryllium-copper, and other alloys melting at considerably elevated temperatures.

Some of the principal advantages offered by die-casting methods are the high rate of production, maintenance of uniformity in dimensions with consequent elimination of machining process, production of intricate sections having contiguous thin and thick

sections, smooth surfaces frequently curtailing considerable reduction in finishing operations, reproduction of ornamental de-

TABLE XVI:—NOMINAL COMPOSITION OF ALUMINUM
DIE-CASTING ALLOYS.

Alloy	Percent of Alloying Elements—Aluminum and Normal Impurities Constitute Remainder.			
	Copper	Silicon	Nickel	Magnesium
13	....	12.0	....	....
43	....	5.0	....	....
81	7.0	3.0	....	....
82	14.0	5.0	....	....
83	2.0	3.0	....	....
85	4.0	5.0	....	....
93	4.0	2.0	4.0	....
218	....	....	....	8.0

signs, and production parts having inserts made integral with the casting. The commercial application of aluminum die-castings are found in household appliances, automotive parts, aircraft parts, electrical equipment, instrument panels and frames, typewriters, rubber molds, etc.

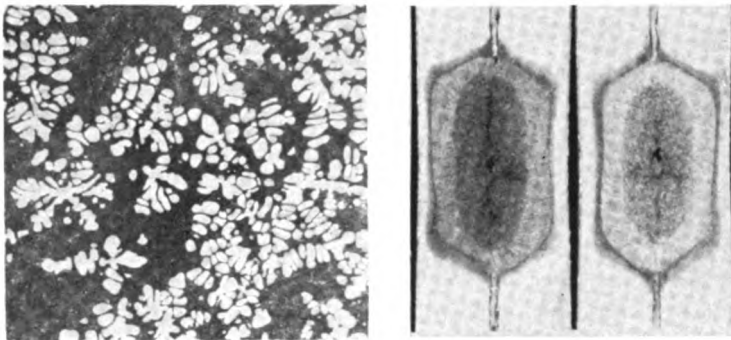


Fig. 157. (a) Micrograph of Aluminum Alloy 13.x100.
(b) Section Through Spot Weld of 24S-T Alclad
Sheet 0.16"-0.16". x 5.8.

Of the aluminum die-cast alloys, Alcoa 13, consisting of 9.5 to 13% silicon, 0.6% copper, 2.3% iron, 0.5% nickel, 0.3% man-

ganese, 0.1% magnesium, 0.17% tin, 0.5% zinc, 0.2% impurities, and the balance of aluminum, is one of the most commonly used in commerce. It is light in weight and possesses high resistance to corrosion. In addition, it has excellent casting characteristics and retains its dimensional tolerance permanently even at somewhat elevated temperatures. It is an all-around general-purpose alloy for large parts that are both intricate and varied in dimensions. Table XVI gives some of the commonly used die-cast aluminum alloys with their nominal compositions.

(c) *Wrought, and Forged Aluminum Alloys.*—Alloys of aluminum can be manufactured into any form of product that any other metal can be formed. For instance, one pound of aluminum can be drawn into 20,000 miles of fine wire, or it can be forged into 30,000 square inches of thin foil. Plates as thick as three inches, rods in excess of eight inches in diameter, seamless tubings of diameters ranging from 0.08 inch to 15 inches are available for diverse uses. Various physical and mechanical requirements and the use into which the wrought, forged, or extruded aluminum alloys may be put are a great deal different from those of cast aluminum products. Because the homogenizing effect through mechanical working and through thermal treatment materially enhances the toughness and the ductility of the metal, the amount of alloying agents required to produce these characteristics may be reduced considerably.

The Aluminum Company of America has produced an aluminum alloy known in commerce as "*Alclad*" having exceptional resistance to corrosion. This property is imparted to the metal by alloying to its surface a layer of high purity aluminum or a special aluminum alloy which is made integral with the core metal in the process. The Alclad alloys 17S-T containing 4.0% copper, 0.5% manganese, and 0.5% magnesium, and 24S-T of a composition 4.5% copper, 0.6% manganese, and 1.5% magnesium are sheet materials of this category of metals. These alloys can be hardened at room temperature after having been solution heat treated in fused sodium nitrate bath. Wrought alloys such as A51S of a composition of 1.0% silicon, 0.6% magnesium, and 0.25% chromium are hardened by precipitation at elevated temperatures, since room temperature aging does not produce an appreciable effect on the hardening.

Table XVII gives a list of wrought aluminum alloys with their nominal compositions. From the table it will be evident that the alloy A51S does not contain any copper and is hardened by precipitation of Mg_2Si (magnesium silicide) in the interstices of the granular structure. Difficult-to-produce and intricate parts are forged from this alloy.

TABLE XVII:—NOMINAL COMPOSITION OF WROUGHT ALUMINUM ALLOYS.

Alloy	Percent of Alloying Elements—Aluminum and Normal Impurities Constitute the Remainder.								
	Copper	Silicon	Manganese	Magnesium	Zinc	Nickel	Chromium	Lead	Bismuth
3S	....	....	1.2	....	....	....	....	....	....
11S	5.5	....	....	....	....	....	....	0.5	0.5
14S	4.4	0.8	0.8	0.4	....	....	....	....	....
17S	4.0	....	0.5	0.5	....	....	....	....	....
A17S	2.5	....	....	0.3	....	....	....	....	....
18S	4.0	....	....	0.5	....	2.0	....	....	....
24S	4.5	....	0.6	1.5	....	....	....	....	....
25S	4.5	0.8	0.8	....	....	....	....	....	....
32S	0.9	12.5	....	1.0	....	0.9	....	....	....
A51S	....	1.0	....	0.6	....	....	0.25	....	....
52S	....	....	....	2.5	....	....	0.25	....	....
53S	....	0.7	....	1.3	....	....	0.25	....	....
56S	....	....	0.1	5.2	....	....	0.10	....	....
61S	0.25	0.6	....	1.0	....	....	0.25	....	....
70S	1.0	....	0.7	0.4	10.0	....	....	....	....

Heat treatment symbols are omitted because of their independence of the composition.

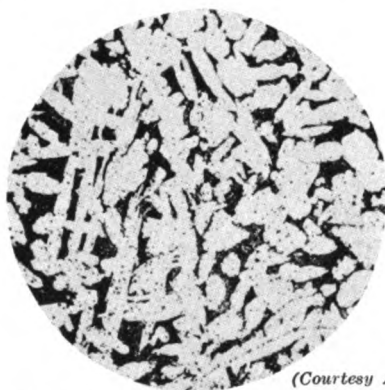
A forging alloy designated as 25S has almost identical properties as that of 17S with slightly superior hot working qualities. It consists of 4.5% copper, 0.8% silicon, 0.8% manganese, and aluminum for the balance. Somewhat similar to the general characteristics of 17S is the alloy 14S of a composition of 4.4% copper, 0.8% silicon, 0.8% manganese, 0.4% magnesium, and aluminum for the balance. The former forging is commonly used for propellers, shafts, and connecting rods for engines of aeroplanes, whereas alloy 14S finds wide application where high strength, hardness, and good resistance to corrosion are desired.

Of the various other processes of fabricating aluminum parts is the one which deserves special interest and is accomplished by forcing the metal under enormous pressures to fill the cavity of a special pressure-resistant die. Unlike the repeated hammering as in a drop forge process, the flow of the metal is brought about by a steady maintenance of pressure over the metal. Since closer dimensional tolerances can be produced by this process, machining for finishing the product is minimized. Akin to this process is the impact extrusion, by means of which collapsible tubes for tooth paste or cosmetics are fabricated. Extrusion processes have contributed materially to simplify aircraft design, and to reduce the cost of production. The products resulting from the process have rendered great structural efficiency owing to their light weight and relatively high strength.

(d) *Aluminum Bronzes*.—Aluminum-bronze is the name implied to copper-aluminum-iron alloys. First introduced in 1870, the alloy has not received as much interest in the industry until last few decades, within which period improved metallurgical and foundry methods have enabled aluminum-bronzes to compete quite favorably with non-ferrous alloys, and steels. Its commercial application resides in the construction of gears for heavy machinery and light automotive structures, aeroplane propeller bolts, landing gear parts, gun mounts, pump parts, and other parts in general commercial and in military aircraft industries.

The alloy consists of 87 to 92 per cent copper, 7 to 10.5 per cent aluminum, 0.20 to 4.0 per cent iron, and 0.2 to 0.5 per cent tin. It combines ductility with high strength, and hence it lends itself to the construction of bearings, feed nuts, bushings, propeller cam rollers, etc. This group of alloys are hard to cast, and require the same foundry technique as alloy steel. In addition, the control of the contents of the various elemental components is very essential, as a small variation in one or the other component may produce a material change in the physical and mechanical characteristics of the resulting alloy. Though the presence of nickel or manganese will decidedly increase the ductility, iron appears to be the chief constituent contributing to the hardness and the tensile strength of the metal. Aluminum bronzes combine strength and ductility comparable to any carbon steel, with added high resistance to shock and atmospheric corrosion.

In an article on "Controlled Aluminum Bronze for Aircraft Parts," *Metal Progress*, December 1940 issue, George K. Dreher, Manager, Ampco Metal, Inc., states, "In aluminum-bronze, the task is to reduce compounds of aluminum and retain metallic purity. Very few elements are capable of doing this. Prudence is required; one part in 8000 of some active deoxidizers is enough to treat and refine the particle size, whereas twice as much will definitely ruin the metal by causing grain boundary segregation. * * * Iron is the most widely used metal for refining the grain size, although nickel, manganese, and zinc each has an effect in varying degrees."



(Courtesy Ampco Metal, Inc.)

Fig. 158. Microstructure of Aluminum-Bronze. $\times 100$.

The pouring temperature of the alloy varies respectively from 1070°C . for heavy castings to 1175°C . for light castings which are chilled during solidification. The physical properties and to some extent the mechanical characteristics of the alloy are considerably improved by chilling, and by heat treatment or hot working. The latter treatment is achieved by heating the casting to a predetermined temperature above that of the eutectoid state, then by cooling through carefully calculated temperature ranges.

A more recent and a very important procedure, known as centrifugal process, involves the pouring of the metal into the mold rotating at high speed and producing a pressure of as high as 100 pounds per square inch on the molten metal. Obviously, the latter process combined with rapid cooling operations will result in superior quality alloy with increased density and conse-

quent long service life. The tensile strength of the alloy varies from 60,000 pounds per square inch for the sand-cast metal up to 110,000 pounds per square inch for the hot-rolled or heat-treated forged material.

2. Magnesium and Its Alloys.—Nearly two centuries have passed since its first recognition as an element, magnesium, though isolated in metallic form in 1831, has gained favor for large scale commercial production only about twenty years ago. Within the past few years great strides have been made in the progress of development of high-strength magnesium products by alloying the metal with other elements such as aluminum, zinc, manganese, cadmium, silver, calcium, nickel, etc. Because the metal and its alloys can be cast, forged, extruded, rolled, and wrought like many important commercial metals, there is an ever-increasing demand for the material in various commercial applications—especially in the fields of terrestrial and aerial transportation—owing to its light weight and moderately high tensile strength and durability.

Magnesium occurs in combination with other elements such as in the form of magnesite (magnesium carbonate), dolomite (carbonates of magnesium and calcium), Epsom salts (magnesium sulphate), and as magnesium chloride from natural salt brines and sea water. It is obtained in metallic form by electrolysis of the molten magnesium chloride, and also of the magnesium oxide in a mixture of fused fluorides. By this method, a purity of 99.8 per cent is easily obtained.

Magnesium is a white metal resembling aluminum but only about two-thirds as heavy (specific gravity 1.74 at 20°C.), and is available in the form of ribbon, wire, extruded strips, and powder. In air it tarnishes slightly, but when ignited it burns brilliantly. Because of its latter characteristic, the metal is widely used for pyrotechnic purpose, for flash-bulbs in photography, and for military applications.

Since pure magnesium has relatively low strength, its commercial applications where more than moderate strength is involved are limited. However, when the metal is alloyed with small amounts of other metals greatly improved mechanical properties are enhanced. Aluminum is the principal alloying element, which increases the mechanical properties of the metal. The addition of

zinc improves the corrosion resistance of the alloy. Manganese, nickel, calcium and other metals, in moderately small quantities, further influence its mechanical properties, which in many ways are comparable to those of commercial aluminum alloys. Aside from its lightness, moderately high strength, and commercial stability against normal atmospheric conditions, the alloy of magnesium has an outstanding property of excellent machinability.

Magnesium alloys can be solution heat treated, and precipitation hardened by forming eutectics. The specific gravity of structural magnesium alloys varies from 1.78 to 1.86. Thus, in view of its lightness, better service performance, and high tensile strength (between 35,000 to 50,000 pounds per square inch), the cost of magnesium alloy on a weight-strength basis is relatively low.

Though resistant to attack by alkalies and by some organic chemicals, almost all acids with the exception of hydrofluoric and chromic acids will attack the alloy. Solutions containing sodium chloride cause rapid corrosion of the metal. Thus, marine constructions of magnesium alloy in contact with the salt water are not recommended. There are a number of good protective coatings that may be applied to the surface of magnesium products which in use are exposed to the atmospheric moisture or salt water.

The principal industrial applications of magnesium alloys reside in their use for making aircraft engine parts, landing wheels, engine crank cases, oil pumps, intake manifolds, envelope folding machines, and reciprocating parts in high speed equipment used in such industries as textile, packaging, printing, and multigraphing. Because of lightness in weight, magnesium alloy products are also used where it is desired to reduce weight such as in portable equipment, pneumatic tools, drilling equipment, grinders, polishers, etc.

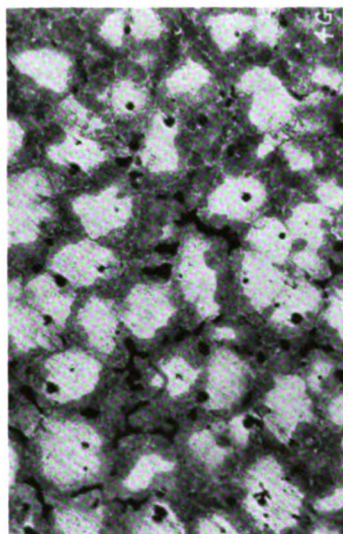
(a) *Magnesium Alloy Castings.*—Because of the high tensile strength, low weight per volume, and excellent machinability of magnesium alloy castings, they are extensively used in aircraft and aircraft engine construction for high-speed rotating or reciprocating parts, thereby ensuring superior performance at low operating costs. The magnesium castings are produced as sand castings, permanent-mold castings, and as die-castings, depending

on the mechanical properties desired, on the intricacy of design, and on the quantity of production. They can be procured with inserts such as bushings, pipes, spheres, bars, etc., cast in the metal. Such inserts are usually of iron or steel; and, wherever non-ferrous metals are required, they are first protected from the alloying action of the molten magnesium by coating them with iron or chromium. Depending on how much molten magnesium will flow around the insert, the material of the latter should be so selected that its melting point is above 1200°F.

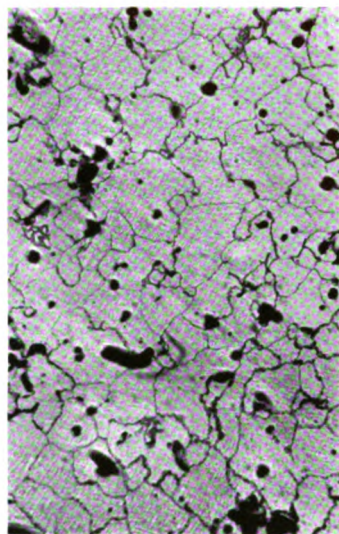
The equipment for casting magnesium is slightly different from that used for casting aluminum in that the gates and the risers are usually larger; an increase in thickness of thinner sections to facilitate the flow of the molten metal is entailed; the molding sand is specially treated to prevent a possible amalgamation; and, finally, provision of a protective flux is made to minimize the oxidation of the metal during melting and pouring. Sections in magnesium alloy castings generally are not less than 5/32 inch thick, as the fluidity of magnesium alloys is not high as in aluminum alloy castings. If thinner sections are required, they are made small and are usually placed in such positions as to allow easy access to the gates.

In selecting the proper alloy for any particular application, consideration should be given to stress conditions the part is intended to withstand, to the tensile strength of the material, to its resistance to shock, fatigue strength, elongation, etc. Of the cast magnesium alloys, a typical composition of excellent general properties is featured by the Mazlo alloy AM265, also known as Dowmetal H, which contains 6.0 per cent aluminum, 0.2 per cent manganese, 3.0 per cent zinc, and 90.8 per cent magnesium. Owing to its high mechanical properties combined with superior casting characteristics and corrosion resistance, which properties are further supplemented by high yield strength and good elongation in the heat treated and aged condition, the material has become a leading commercial alloy especially in aircraft industry.

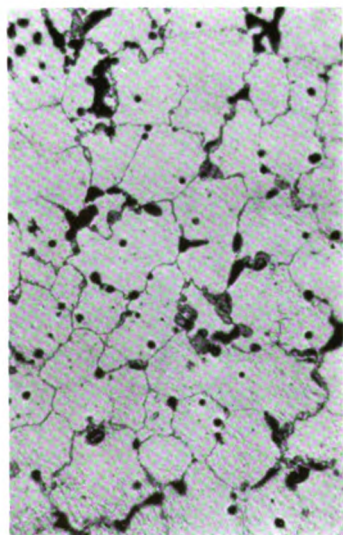
A newly developed magnesium alloy, designated as AM260 or as Dowmetal C, having a nominal composition of 9.0 per cent aluminum, 0.1 per cent manganese, 2.0 per cent zinc, and 88.9 per cent magnesium, possesses an excellent combination of good foundry characteristics, high mechanical properties, and excellent



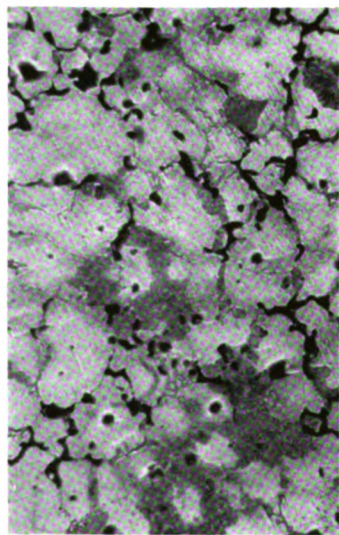
(a) As Sand-Cast State.



(b) Thermal Treated to T4 State.



(c) Thermal Treated to T6 State.



(d) Aged at 450°F. for 4 Hours.

Fig. 159. Microstructure of Dowmetal H. $\times 100$.

stability. It is available in either solution heat treated condition or in heat treated and aged temper.

A list of typical compositions of magnesium alloys is given in

Table XIX, each one of which alloys meets a specific requirement. In general, typical applications of these alloys primarily reside in their use for parts which are highly stressed and complicated as in aircraft engines and landing wheels, and in those which have high-speed reciprocating parts requiring high strength combined with resistance to sudden shocks and vibrations.

TABLE XIX:—NOMINAL PER CENT COMPOSITION OF
MAGNESIUM ALLOYS.

Amer. Mag. Corp.	The Dow Chem. Co.	Mg	Al	Mn	Zn	Si	Cd	Ag
AM246	Dowmetal B	87.9	12.0	0.1	....	....	...	...
AM260	Dowmetal C	88.9	9.0	0.1	2.0	....	...	...
	Dowmetal E	93.8	6.0	0.2	....	....	...	...
	Dowmetal FS	95.8	2.7	0.2	1.0	....	...	...
AM240	Dowmetal G	89.9	10.0	0.1	....	....	...	...
AM265	Dowmetal H	90.8	6.0	0.2	3.0	....	...	...
AM57S	Dowmetal J	92.6	6.5	0.2	0.7	....	...	...
AM230	Dowmetal K	89.4	10.0	0.1	....	0.5	...	...
	Dowmetal L	93.7	2.5	0.3	....	....	3.5	...
AM3S	Dowmetal M	98.5	....	1.5	....	....	...	...
AM58S	Dowmetal O	90.8	8.5	0.2	0.5	....	...	...
	Dowmetal R	90.2	9.0	0.2	0.6	....	...	...
AMC74S	Dowmetal X	93.8	3.0	0.2	3.0	....	...	...
	Dowmetal Z	89.1	2.6	0.2	2.6	....	...	5.5
AM52S		95.3	3.0	0.1	1.3	0.3	...	...

Both of the alloys AM265 and AM260 can be sand cast, but the latter and another alloy AM240 can also be produced as permanent-mold castings. The latter castings are characterized by fine grain structure and, therefore, afford close dimensional tolerances. The permanent-mold castings in general do not require as much machine finishing as sand castings and can be formed with thinner walls or webs. Where greater intricacy of interior design is desired, semi-permanent molds using sand cores are of added advantage. This type of casting process which will permit the production of quantities in excess of 500 pieces will become more economical than sand castings. These castings are heat treatable, and when they undergo the treatment, they acquire superior qualities of strength, resistance to corrosion, and pressure tightness.

Magnesium alloys are also adaptable to die casting, achieving

maximum lightness owing to the possibility of producing thinner sections. The surfaces of die-cast parts being very smooth, little or no machining is necessary. This is also aided by the dimensional accuracy ranging from 0.0015 to 0.002 inch per inch. Because of its good casting characteristics, the Mazlo alloy AM263-C is the general choice where also maximum lightness, accuracy of dimension, and substantial reduction in machining are desirable. When manufactured in sufficiently large quantities, die-cast parts, though their first cost due to special equipment is somewhat higher than for sand castings, become not only preferable because of their high mechanical qualities but also because of their production on a more economical basis. Quantities ranging from 500 to 1000 parts will frequently be sufficient to liquidate the additional die cost over that of sand casting. Typical uses of magnesium die-casting are indicated in aircraft engine parts, vacuum cleaner parts, binocular frames, automotive parts, typewriter parts, and other articles of light and intricate fabrications.

(b) *Wrought Magnesium Alloys.*—Products of magnesium alloy are also available in a number of commercial wrought, and forged forms. As mentioned previously, these alloys have been developed to meet specific demands. Their tensile strengths range from 30,000 to 50,000 pounds per square inch. Characteristic of these alloys are Mazlo AM3S or Dowmetal M, consisting of 1.5 per cent manganese, and 98.5 per cent magnesium, used for moderately stressed aircraft parts where good forming quality combined with superior welding characteristics are essential.

Dowmetal J (AM57S) and Dowmetal O (AM58S) are widely used for extrusion and press forging. Where high strength and high ductility are required as in extrusion products, sheets, plates, and bars, AM52S is specified. Other applications of magnesium alloys are exemplified in their use for aircraft propellers and gasoline tanks, fuel line fittings, engine cowlings, and other highly stressed parts.

For still other highly stressed parts requiring light weight and resistance to intermittent shock, magnesium alloy forgings are preferred. The alloy is frequently used for parts subject to vibration where stress concentrations are at constant reversals. It should be noted that indentations of any nature characterized by tool marks, deep scratches, and extraneous marks by die-

stampings will cause the metal to become susceptible to failure in service. The latter condition may also be favored by sharp corners, and notches, which greatly affect the endurance limit.

To protect the surface of the metal from the atmospheric saline attack, almost all magnesium castings and forgings are impregnated with a protective coating such as potassium dichromate bath, which also serves as an excellent paint base.

(c)—*Surface Protection of Magnesium Alloys.*—Indiscriminate exposure to inland atmospheric conditions causes gradual darkening of the surface of magnesium alloys. A thin film consisting of magnesium hydroxide and magnesium carbonate usually, when formed due to this exposure, retards to a considerable extent subsequent atmospheric attack. The rate of corrosion is a direct function of the humidity and the temperature; and, under a high magnitude of these conditions the salt air along the coast greatly affects the acceleration of the corrosion rate. For these reasons, it is advisable that a suitable surface protection such as a coating of clear resin lacquer or other chemical coatings presently to be described are applied to the exposed surfaces. Where necessary, the chemical treatment is supplemented by appropriate paints, synthetic resin enamels, etc. Surface electroplating with non-corrosive type metals, or spraying with metallic coatings, are also employed but so far the methods have not met with commercial success.

The importance of surface protection is further indicated by the electrolytic corrosion resulting from contact of magnesium alloys with other metals placed in chemical solutions ordinarily considered as non-corrosive. In assemblies comprising magnesium alloys and copper, copper-bearing alloys, steel, monel, nickel, tin, lead, solder, and similar alloys, adequate electrical insulation must be provided in order to obviate the tendency of an electrolytic action that may be set up by contact potential resident between any two unlike metals. Magnesium is strongly electropositive to most structural metals, and since aluminum, cadmium, and zinc are also electropositive to a high degree relative to magnesium, these latter metals may be used as a coating for the above-mentioned structural metals to produce the least electrolytic attack.

In Table XX is given a series of elements arranged in their

decreasing electromotive force values, which will indicate to the reader the importance of discrimination in the selection of metals to be used in conjunction with magnesium alloy assemblies.

TABLE XX:—THE ELECTROMOTIVE FORCE OF
IMPORTANT ELEMENTS.

Electropositive Elements			Electronegative Elements	
1. Li	11. Fe	21. As	1. S	10. Cl ₂
2. K	12. Cd	22. Cu	2. C	11. O ₂
3. Ba	13. Tl	23. Ag	3. B	12. F ₂
4. Ca	14. Co	24. Hg	4. N ₂	
5. Na	15. Ni	25. Pd	5. Se	
6. Mg	16. Sn	26. Pt	6. P	
7. Al	17. Pb	27. Au	7. S	
8. Mn	18. H ₂	28. Ir	8. I ₂	
9. Zn	19. Sb	29. Os	9. Br ₂	
10. Cr	20. Bi			

The usual surface protection for magnesium alloys consists of cleaning, treating with a suitable chemical solution, priming, and finally painting. The American Magnesium Corporation proposes the accompanying formulas for surface treatment, and which have been proved to give very satisfactory results on a commercial scale.

After machining and forming operations, the parts require a thorough cleaning to remove dirt, oil, or grease before an appropriate paint can be applied. This may be accomplished by rinsing the parts in naphtha, gasoline, carbon tetrachloride, or in trichlorethylene. But, a more rapid and economical method embodies the cleaning by use of an alkaline solution given below:

AMC SURFACE CLEANER

Sodium Carbonate	3 ounces
Sodium Hydroxide	2 ounces
Soap	1 ounce
Water to make	1 gallon

The parts are cleaned in the above solution at boiling temperature, thoroughly washed in cold running water, and rinsed in hot water to facilitate drying.

After having undergone a cleaning treatment in the above solution, the parts are immersed in a Dichromate Bath, also

known as Chrome Pickle, to further passivate the surface of the metal. This treatment produces an etching effect on the surface and further acts as an excellent paint base. An effective solution which may be employed at room temperature or it may be heated as high as 150°F. to increase the rate of reaction can be made in accordance with the following formula:

AMC TREATMENT A

Sodium Dichromate ($\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$)	.... 1.5 pounds
Nitric Acid (Sp. Gr. — 1.42)	..... 1.5 pints
Water to make	..... 1.0 gallon

The articles to be treated are immersed in this solution for 30 seconds to 2 minutes, depending on the concentration or the strength of the solution, after which process they are taken out and drained for 5 to 20 seconds. They are then rinsed in cold water followed by immersion in hot water at 180°F. to facilitate drying. Magnesium sand castings are usually treated in this solution before they are delivered to the user.

Another dichromate bath recommended for the purpose is the *AMC Treatment B*, which is applied to the surface of the thoroughly degreased and cleaned magnesium alloy parts as follows:

AMC TREATMENT B

The parts to be treated are immersed for 5 minutes in a boiling solution of sodium hydroxide containing 2% *NaOH* by weight. They are then thoroughly rinsed in hot running water and immersed for one-half hour in a boiling solution of the following bath:

Potassium Dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$)	..... 2 ounces
Ammonium Sulphate ($(\text{NH}_4)_2\text{SO}_4$)	..... 4 ounces
Ammonium Dichromate ($(\text{NH}_4)_2\text{Cr}_2\text{O}_7$)	..... 2 ounces
Distilled water to make	..... 1 gallon

After the treatment, the parts are thoroughly washed in hot running water, and dried in an oven at a temperature of about 140°F.

It is very essential that the acidity of the solution is checked frequently by using bromo-cresol purple indicator to make sure that the p^{H} value of the bath is kept between 6.0 to 6.4.

All Mazlo magnesium alloys including AM3S can be treated in

a solution designated as *AMC Treatment J*, which further imparts a decorative finish to the parts in addition to its effectiveness as a base for paint. It is found especially useful for assemblies consisting of two or more different alloys, as it will adhere to the alloys readily because of its normalized solution potential.

AMC TREATMENT J

Aluminum Nitrate [$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$]	500.0 grams
Potassium Dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$)	50.0 grams
MPD 189 Wetting Agent (By Du Pont)	2.0 grams
Water to make	1000.0 Cc

Directions to Use *AMC Treatment J*:—The castings are immersed in 1.5 per cent solution of sulphuric acid for 1 minute, and then taken out and boiled in a 5 per cent solution of sodium hydroxide for 5 minutes. For machine castings, the acid treatment is dispensed with, but grease or oil is first removed by any of the above-given organic solvents and then boiled in 5 per cent sodium hydroxide for 5 minutes. The parts are then ready for processing in the *AMC Treatment J* for 30 minutes at a temperature between 98 to 100 degrees centigrade, near the boiling point of water. Subsequent to the treatment, the articles are rinsed in cold water and dried. (Note:—The hydrogen ion concentration should be maintained throughout the processing period at a pH value of 2.0 to 2.9.)

This treatment, and those preceding, in general impart a decorative bronze or light brown finish to the article. After the dichromate coating is dry, it is recommended that the parts be immediately painted with a suitable paint such as a good quality enamel or lacquer.

The Chrome-Bath treatment for forgings, sheets, and extrusions is same as above with the exception of the precleaning process, which embodies the degreasing, and boiling the material for 2 to 5 minutes in a 5 per cent solution of sodium hydroxide.

3. Important Copper Alloys in Aircraft Application.—Copper is one of the prehistoric elements, and is claimed to have been in commercial use for more than 6,000 years. It occurs chiefly in the form of sulphide, oxide, carbonate, carbonate-hydroxide, silicate, and sulphate. In metallic form, it possesses a reddish-colored bright luster, and is very ductile, malleable, and a good

conductor of heat and electricity. It is obtained by concentrating the ore, and then smelting it, or by leaching. The pure metal is invariably refined by electrolysis to a purity of 99.95 per cent. It is chiefly used in electrical industry as current conductor or wire, electrical fixtures, kitchen utensils, radiators, tubings, for ornamental purposes, in a great number of alloy forms, and is a valuable entity in chemical industry.

Like most other alloy bases, when copper is alloyed with small amounts of other elements its strength, hardness, ductility, and other physical characteristics are affected to a great extent. The principal alloying elements are zinc and tin. Commercial brass consists of 10 per cent zinc and 90 per cent copper, whereas 1.0 to 2.0 per cent zinc, 4.0 to 10.0 per cent tin, and 88.0 to 95.0 per cent copper alloys are known as bronzes by various names. Other elements which also alloy with copper to form useful combinations are aluminum, nickel, beryllium, lead, phosphorus, silicon, silver, and gold.

The majority of the above elements are soluble in copper to an appreciable degree, and form alloys varying in tensile strength from 30,000 to 240,000 pounds per square inch. Lead is the least soluble in copper yet the most useful element to form an alloy material widely used in heavy duty bearings superior to white metal bearings at elevated temperatures as used in railroad service, and in automotive and aircraft engine bearings. Manganese and aluminum have strengthening effect and further impart corrosion resistance to the alloy. The presence of small amounts of silicon and nickel considerably improve the latter property of the alloy, while phosphorus in very minute quantities greatly enhances the casting qualities and surface characteristics. The electrical conductivity of copper, however, is considerably decreased by the addition of any of these alloying elements.

(a) *Copper-Aluminum Alloys.*—We have already discussed in Section 1 (d) some of the important phases of copper-aluminum alloys under the heading of "*Aluminum Bronzes.*" The relative compositions of these alloys together with some of their characteristics have also been discussed. Nevertheless, in this section we shall make an attempt to review some of the important uses of copper-aluminum alloys in a general aspect especially for aircraft requirements.

Aluminium bronzes in their sand-cast, die-cast, extruded, or centrifugally-cast condition are particularly suitable for applications where the desirability of hardness, resistance to wear, and vibration-damping properties are essential. Other outstanding qualities of this alloy reside in its possessing an exceptionally high resistance to corrosion, superior wearing qualities, and in having a considerably lower density than some of the important non-ferrous alloys. It weighs 0.27 pound per cubic inch, and is about 20 per cent lighter than tin bronzes. On a strength-weight basis, then, the alloy adequately lends itself to the use of some of the most critical structural parts in an aircraft. For instance, blade bushings for propellers, cam-actuating rollers, and couplings and other parts for operation with steel gears and bearings, brackets for pivoting aerial machine guns, tail wheel trunnion, etc., some of which formerly were made of beryllium-copper alloy at a higher cost are now made of copper-aluminum alloy.

In view of its special founding requirements arising from its tendency to undergo high shrinkage and also to form dross upon exposure to the atmosphere, the cost of casting aluminum-bronze is relatively high. The high shrinkage of the alloy, however, does not ordinarily give rise to shrinkage cracks, owing to its high strength at elevated temperatures. These adverse tendencies can be further overcome by adequately designed patterns including the molds, chills, gates, and risers. Turbulant pouring of the molten metal into the mold must be rigorously avoided, as a very porous condition will result.

The addition of iron such as found in Type 89-10-1 alloy, which consists of 1.0 per cent iron, 10.0 per cent aluminum, and 89.0 per cent copper, the tensile strength and other mechanical qualities in general of the alloy are materially increased. When heat treated at 1700°F., and tempered at about 700°F. subsequent to quenching in water, the tensile strength of the alloy rises to as high as 95,000 pounds per square inch. These alloys are not affected to an appreciable degree by exposure to sea air, and to industrial atmospheres, and by contact to sea water, weak acid solutions, and to many neutral salt solutions.

(b) *Copper-Beryllium Alloys.* — Although copper-beryllium alloys and their metallurgical characteristics have been definitely known for over twenty-five years, the application of the material

has not received as great an impetus as within the last ten years or so. With the discovery that the addition of a small quantity of beryllium to copper forms an alloy which upon precipitation hardening gives a Brinell value as high as 425, the alloy has become to occupy a significant place among important metals of industry. Its superior tensile strength with a combination of high ductility, and wear resistance, renders the alloy desirable qualities such as required in the construction of aircraft engine parts,

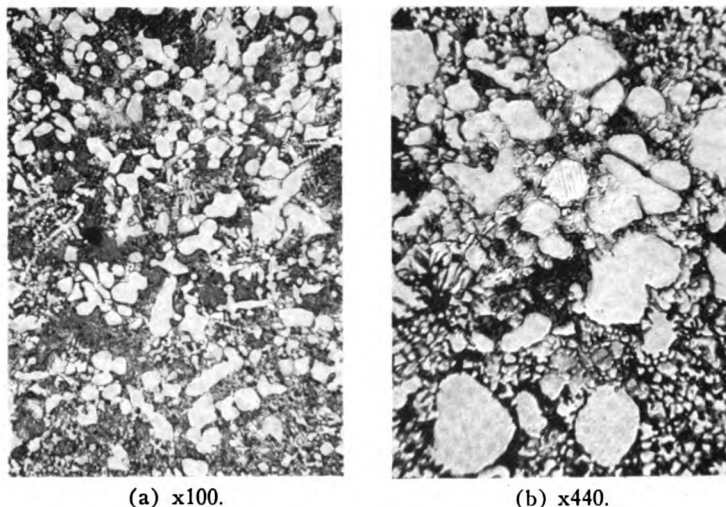


Fig. 159A. Microstructure of Beryllium-Copper Alloy.

aircraft radios, and delicate parts of electrical instruments, owing to its non-magnetic characteristics.

Beryllium occurs chiefly as beryllium-aluminum silicate, and also as beryllium oxide. First isolated by Wohler in 1828, beryllium in its metallic form, which is prepared by electrolysis, resembles the element magnesium both in physical appearance and in chemical properties. It has a specific gravity of 1.85, and melts at 1350°C . Its alloying characteristics principally with copper to produce an increased hardness, strength, and resistance to corrosion are what have given the beryllium-copper alloys much publicity in the present metallurgical industry. Despite the high cost of production of the metal from its ore, beryllium alloys are relatively inexpensive in view of the small percentage.

between 0.1 to 3.0 per cent, of beryllium required in hardening its commercial alloys.

The nominal compositions of beryllium-copper alloys range from 1.75 to 2.75 per cent beryllium, 0.1 to 0.5 per cent nickel, 0.1 to 0.25 per cent iron, 0.4 to 1.0 per cent aluminum, 0.1 to 0.6 per cent arsenic, and about 0.5 per cent silicon. The presence of nickel in the alloy produces grain refinement with consequent increase in ductility, whereas aluminum and arsenic are claimed to improve the forming characteristics of the alloy.

Copper-beryllium products may be produced by die-casting, extrusion, drawing, forging, and by other methods. The alloy is softened by thermal treatment between 750°C. to 800°C. and subsequent quenching in water, which procedure retains the alpha solid solution phase of beryllium. By reheating the alloy at temperatures ranging from 250°C. to 335°C. causes the hardening of the material with the precipitation of the hard delta phase. Because these alloys soften above their hardening temperatures (maximum of 350°C.) parts fabricated of this material should not be used at elevated temperatures. Special alloys of beryllium containing small amounts of cobalt or chromium, in addition to larger percentage of copper, precipitation harden at 425°C. to 500°C., and, therefore, they may be employed at higher temperature ranges than the usual binary combinations.

An alloy commercially produced by Cooper-Wilford Beryllium, Ltd., and designated as Beralite-35 is claimed to be lighter (sp. gr.—2.3) than aluminum (sp. gr.—2.7) and about 20% heavier than magnesium alloy of specific gravity 1.89, but equaling and slightly exceeding the ultimate tensile strength of the latter. It is designed particularly where modulus is the determining factor, and is generally employed in the aircraft industry for engine parts, superchargers, pistons, and impellers. The 25 to 50 per cent beryllium content in aluminum is of particular consequence because of its stiffening characteristics. The application of this latter alloy embodies the production of engine parts, including pistons, connecting rods, diaphragms, valve actuating mechanisms, and other structure where high modulus, and resistance to wear and fatigue are the designing factors.

(c) *Other Copper Alloys.*—Copper occurs in many iron ores, and is frequently carried through the reduction process inten-

tionally. It is also added as an alloying element to pure iron to increase its corrosion resistance and yield strength, but the ductility, especially in carbon steels, is lowered as the copper content is increased. A small amount of copper up to 0.65% is sufficient to effect a material increase in the electrical resistance, also improving the magnetic properties of hard steels which can be permanently magnetized.

The mechanical properties of copper-steel are found to become improved by the addition of small quantities of manganese, nickel, molybdenum, and sometimes chromium. The nominal composition of a typical copper-steel alloy is given as 0.08 to 0.35% carbon, 0.15 to 1.0% manganese, 0.25 to 1.30% copper, 0.25 to 2.0% nickel, and other elements (when present) such as molybdenum 0.05 to 0.25%, silicon 0.25%, phosphorus up to 0.15%, and chromium 0.25%.

A very useful alloy known as manganese-bronze, consisting of 50 to 60% copper, 0.4 to 1.5% aluminum, 0.8 to 3.5% manganese, 1.0 to 2.0% iron, 0 to 1.5% tin, and the balance zinc, is widely used in marine construction. Ship propellers, electrical equipment, trunnion bearings or bushings, and parts that are in constant exposure to atmospheric or sea water corrosion conditions are fabricated of this alloy. Its non-magnetic property together with moderately high mechanical qualities render the metal additional usefulness. The alloy develops a tensile strength between 65,000 to 110,000 pounds per square inch.

Phosphor-bearing metals commercially known as gun-metal, bearing bronze, etc., can be modified by addition of tin, lead, or zinc, improving the operative, wearing, and casting qualities of the alloy. In this respect, the presence of lead occupies a place of first magnitude. The 80-10-10 alloy, containing 80% copper, 10% lead, and 10% tin, is extensively used as a bearing metal, and in parts that are in constant frictional service.

Among the corrosion resistant alloys of copper is the copper-silicon combination, which lends itself to special importance among metals of commerce because of its additional properties of high strength and toughness identical with mild steel. The alloy can be cast, forged, extruded, rolled, or stamped, and is extensively used in the manufacture of small arms ammunitions, fans, processing tanks, marine hardware, boilers, blowers, ventilators,

and other products exposed to corrosion conditions in operation. The nominal composition of a typical copper-silicon alloy is 95% copper, 3.0% silicon, 1.0% manganese, 0.25% lead, and tin and zinc up to 0.75%.

4. Nickel and Related Nickel Alloys.—Nickel is a silvery-white, hard, and malleable metal. It has fairly high thermal and electrical conductivities, and is somewhat magnetic, belonging to the cobalt and iron group in the periodic system. It is chiefly derived from nickeliferous pyrrhotite mined in the Sudbury district in Ontario, Canada. It has an atomic weight of 58.69, specific gravity 8.90, and a melting point of 1452°C.

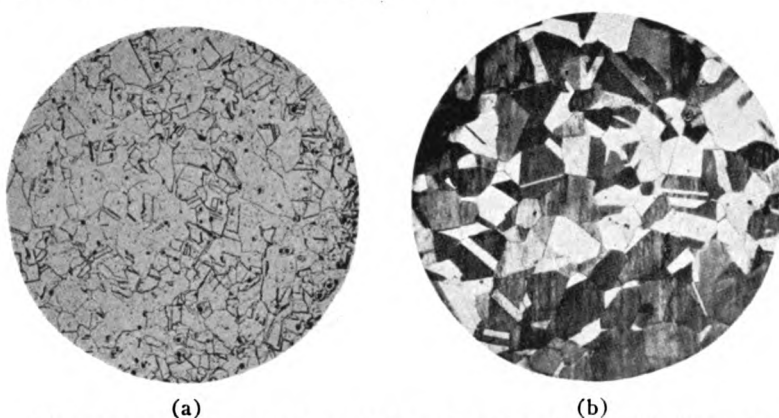


Fig. 160. (a) Microstructure of Annealed Monel, and (b) That of Monel Forging. $\times 100$. (Courtesy The International Nickel Co., Inc.)

The commercial applications of nickel chiefly reside in its numerous alloys which it forms with other metals such as copper, molybdenum, chromium, iron, tungsten, manganese, and silicon. Of these, nickel-silver, nominally consisting of 20% nickel, 6% zinc, 5% lead, 4% tin, and copper for the balance, forms an alloy highly resistant to corrosion by foodstuffs and by atmospheric conditions. Its further uses are indicated in springs, electrical resistors, jewelry, tableware, and other important hardware.

Some of the more important nickel alloys available by various commercial names are Monel, Inconel, Nichrome, Ni-Resist, Ni-Hard, etc. Of these, Monel, having a nominal composition of 67% nickel, 30% copper, 1.4% iron, 1.0% manganese, 0.15% carbon, and 0.1% silicon, possesses high tensile strength and

hardness, with good resistance to corrosion. It is extensively used in power equipment, petroleum industry, household fixtures, such as kitchen sinks and equipment, in textile and food industries, equipment in the manufacture of pulp and paper and for handling steel in pickling processes. Monel may be produced in the form of plates, rods, wires, and castings. In an annealed form, its tensile property rises as high as 100,000 pounds per square inch.

Monel in its modified forms is manufactured under the trade names of K-Monel, R-Monel, H-Monel, and S-Monel. The K-Monel, consisting of 66% nickel, 29% copper, 2.75% aluminum, and 0.9% iron, is a non-magnetic and age-hardening alloy, with a tensile strength from 100,000 psi for hot-rolled to 155,000 psi for cold-drawn materials.

The R-Monel has a nominal composition of 67% nickel, 30% copper, and 0.035% sulphur, and is a free machining grade of material particularly adaptable for use in automatic screw machines. Its mechanical properties and resistance to corrosion remain the same as for Monel.

The H-Monel and S-Monel are both silicon alloys containing respectively 3% and 4% silicon in addition to the elements found in cast Monel. These alloys provide increased ductility, good casting characteristics, and high Brinell hardness developed by suitable thermal treatments.

Inconel has a composition of 79.5% nickel, 0.2% copper, 6.5% iron, 0.25% manganese, 0.25% silicon, 0.08% carbon, 0.015% aluminum, and 13.0% chromium. It is believed that carbon in this alloy occurs as Cr_7C_3 . Like Monel, it is stress-equalized at an annealing temperature of 1000°F.

5. Steel and Its Various Forms.—Steel consists of a solid solution of iron carbide (Fe_3C) in iron having a carbon content not exceeding 2%. It is formed by purifying iron and adding varying amounts of carbon, sulphur, manganese, phosphorus, chromium, nickel, molybdenum, and other elements depending on the type and character of steel desired.

As referred to above, iron is the precursor of steel and in its pure state it is a silver-white metal with high ductility and high magnetic properties. It is the most abundant of metals (with the exception of aluminum) and chiefly occurs in nature as hematite (Fe_2O_3), which is converted into the metallic form by reduction

with carbon. The pure metal is obtained by electrolysis of iron sulphate, and has an atomic weight of 55.85, specific gravity of 7.85 - 7.88, and a melting point of 1535°C. Although iron forms various alloys with the same alloying elements that enter into the forming of different types of steel and has numerous commercial applications, the accompanying discussions will be confined primarily to the treatment of various alloy steels.

Like non-ferrous alloys, the properties of alloy steel are dependent on the chemical composition of the metal and are largely determined by the treatment it receives. For instance, the chief ferritic component in steel is iron carbide which produces toughness and strength in steel. The latter properties are further aided by adequate thermal treatment and quenching, or by proper annealing of the metal, thus varying the amount of solution of the iron carbide to a predetermined value. When the body-centered alpha structure is transformed into the face-centered gamma structure in the austenitic form, a considerable amount of carbon can dissolve in the metal.

While the amount of carbon in steel generally influences its mechanical properties, the carbon content may be reduced by the adoption of alloying small amounts of other elements such as copper, silicon, nickel, molybdenum, vanadium, manganese, or chromium to obtain the same strength-giving quality of carbon. Tests have definitely proven that as low as 0.2% copper in steel improves its corrosion resistance. Nickel and phosphorus bear similar effect on the metal, whereas chromium in small quantities definitely increases the strength and in larger amounts a high resistance to corrosion ensues. Molybdenum acts in the capacity of refining the grain size and hence increasing the strength of steel, while aluminum and infrequently titanium are employed to improve its ductility. The presence of manganese in steel directly increases the latter's tensile strength by combining with carbon and forming manganese carbide (Mn_3C), and lowering the transformation temperatures. Manganese also combines with sulphur to form MnS , eliminating the harmful effect that sulphur forms in the metal.

Steels are classified in general into various groups under the headings of Carbon Steels, High Manganese Steels, Nickel Steels, Nickel-Chromium Steels, Molybdenum Steels, Chromium

Steels, Chromium-Vanadium Steels, Tungsten Steels, and Silicon-Manganese Steels. To identify their compositions, these steels are assigned various S.A.E.* Steel Specification numerals, which generally consist of 4 or 5 digits. The prefix *X* denotes a variation in the range of the alloying elements. For instance, the first digit indicates the type of the steel, the second indicates the approximate percentage of the predominant alloying element, and the last two or three digits usually give the average carbon content per hundredth of 1%. Thus, in the chrome-molybdenum alloy designated as 4130, the first digit "4" indicates a molybdenum steel, "1" gives the approximate percentage of the predominant

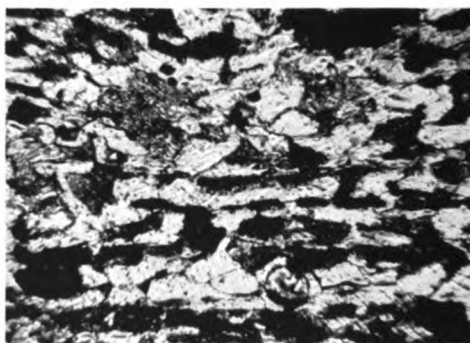


Fig. 161. Microstructure of Carbon Steel. $\times 440$.

element Chromium (1%), and "30" refers to carbon content as 0.30% (0.25 - 0.35%). However, to avoid confusion, the second and third digits are modified in some instances in order to subgroup the original classification.

In considering S.A.E. steels by types, reference will be directed first to carbon steel, the average composition of which is 0.1 to 1.05% carbon, 0.20 to 1.65% manganese, 0.040% phosphorus, and 0.050% sulphur. These steels are suitable for applications where high strength and high plasticity are not the designing factors. They are ordinarily used as constructional materials such as for buildings, bridges, rivets, and some types of pressure tanks. Where toughness and resistance to shock are of

* Society of Automotive Engineers, Inc.

primary importance, low carbon steel range is used as for tool steel.

A subgroup of carbon steels are the free-cutting steels which are also of low carbon content and are generally finished by cold drawing. They are particularly adapted to screw machine stocks, and for machining purposes. The presence of manganese sulphide, iron sulphide, and slag tends to embrittle the metal, while the grain size has direct bearing on the machinability. The steels with high phosphorus content further improve the last-given property of the material.

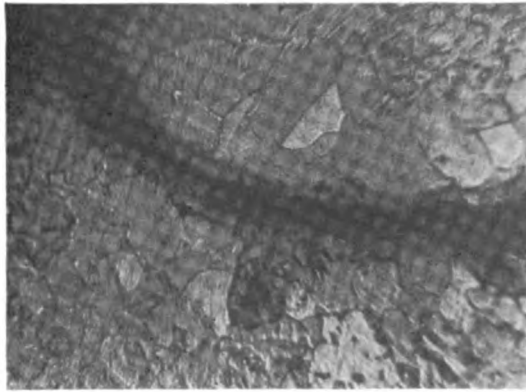


Fig. 162. Micrograph of a Carbon Steel Bar Showing Quenching Crack. x440.

Alloy steels may be grouped into low alloy, medium alloy, and high alloy steels, either in accordance with their functional significance or from the standpoint of their chemical compositions. On the basis of latter consideration, low alloy steels contain less than 1.65% total alloying elements, and are used for structural purposes after having been normalized; the medium alloy steels containing up to 8% of alloying elements are used for machine parts in carburized condition; and, high alloy steels are characterized by total alloying elements exceeding 10%, and find extensive application where resistance to corrosion (stainless steel), service wear, and to heat are primary requirements.

Manganese as an alloying element in steel produces marked effect on the hardenability and tensile strength of the metal. As

was mentioned above, the combination of manganese with carbon especially in high carbon steel to form Mn_3C and subsequently to become associated with Fe_3C further improves the tensile quality of steel with slight sacrifice in ductility.

Heat treatment of manganese steels should be carried out with special scrutiny as indiscriminate heating and cooling cause excessive brittleness, thus militating against the strength-producing characteristics of the alloying elements. The deleterious effect of the procedure is further indicated in the production of grinding cracks particularly in sections consisting of five or six inches thick due to unequal cooling.

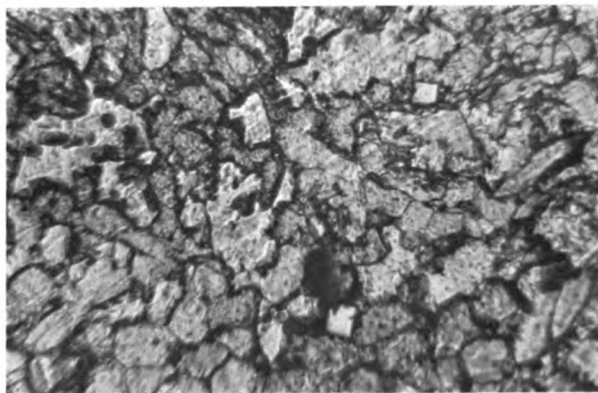


Fig. 163. Microstructure of Medium Alloy Steel Showing Cubic Crystals of Zirconium. $\times 440$.

The nominal chemical range of manganese steels, for instance, that of 1330, is 0.20% carbon, 1.75% manganese, 0.040% phosphorus, 0.040% sulphur, and 0.25% silicon. Because of its non-magnetic nature, manganese steel is usually employed for parts of electrical equipment where a high-strength non-magnetic metal is required. The alloy is employed in transformer parts, railway frogs, rock crushers, conveyor chains, steam shovels, gears, sprockets, pinions, etc. In the heat treated condition, manganese steel is machined with great difficulty, and therefore, its operation is usually carried out by grinding tools. In general, the metal possesses a high wear-resisting property contributable to cold working processes which the metal undergoes during manufacture.

It is found, however, that the addition of nickel to steel increases the strength, toughness, and hardness of the metal without corresponding loss in its ductility. Nickel forms a solid solution in iron in all proportions in both the molten and solid states. Its presence in steel further depresses the critical temperature range, lowering the ratio of the eutectoid phase, and further reducing the critical rate of hardening so that the alloy may be quenched in oil with decreased tendency for cracking or warping. Because nickel does not interfere with nucleation process by retarding the rate of grain growth at sustained high temperatures during thermal treatment, the phenomenon lends itself to the production

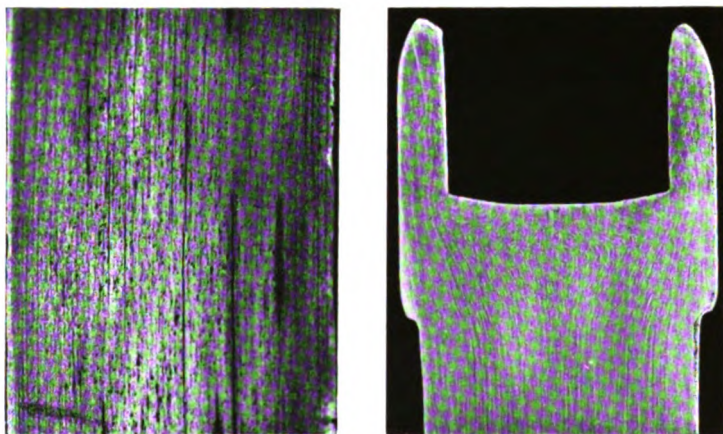


Fig. 164. Macrograph of a Forged Steel Showing (Right), Flow Lines; and (Left), Laminations Due to Poor Material. $\times 1.5$.

of excellent case hardening of the steel. The element further increases the impact toughness of steel and its resistance to corrosion and to fatigue.

An average composition of nickel-steel, for instance that for S.A.E. 2330, may be given as 0.30% carbon, 0.70% manganese, 0.040% phosphorus, 0.040% sulphur, 0.25% silicon, and 3.60% nickel. The alloy develops a yield strength of 65,000 to 150,000 psi, and a tensile strength of 95,000 to 180,000 psi, with an elongation between 12.0 to 28.0%, and is generally used for locomotive boilers, armor plates, bolts, shafts, studs, railway axles, bridge members, and other structural forgings or castings.

About twenty years ago, a new type of corrosion resistant

steel was commercially introduced as "stainless steel," which chiefly consisted of chromium up to 14 per cent. At present, high alloy steels of over fifty different compositions are in industrial use, each alloy serving a particular application. The addition of chromium imparts high corrosion-resisting qualities to steel, and in conjunction with nickel the range is still further extended. Some of the other elements that are added to those already present in ordinary stainless steel alloy are aluminum which influences the scaling tendency of the metal at high temperatures, columbium and titanium prevent intergranular corrosion, manganese increases ductility and toughness, selenium improves the machining prop-

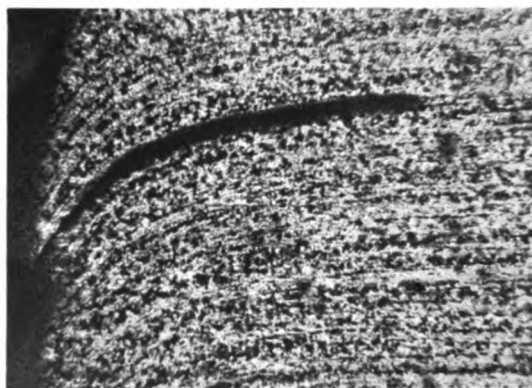


Fig. 165. Macrograph of Chrome-Molybdenum Steel Showing Stamping Crack. $\times 30$.

erties, silicon improves the welding qualities, and tungsten prevents intercrystalline attack and increases the tensile strength of the alloy.

Stainless steel type alloys are used in cutlery, kitchen utensils, ball-bearings, chains, turbines, valves, sprockets and gears for under-water use; and, in sheet and rod forms in numerous fields of applications including all types of medical instruments. A typical stainless steel composition will consist of 0.20 to 0.25% carbon, 6.0 to 25.0% nickel, 0.40 to 4.0% manganese, 8.0 to 25.0% chromium, 0.50 to 2.50% silicon, and the balance of iron.

Development of secondary hardness on tempering may be produced in steel by the addition of molybdenum. Where deep hard-

ening is a designing factor, molybdenum imparts a high endurance limit with added improvement in resistance to creep at elevated temperatures. By possessing a high tempering temperature, the metal contributes to the development of high toughness and resistance to corrosion.

Upon adequate thermal treatment, molybdenum steel possesses greater hardenability than carbon steel having identical quantity of carbon, and similarly will develop depth hardening as in carbon steels. The presence of the alloying element in steel becomes a function of the rate of nucleation and of retardation of grain

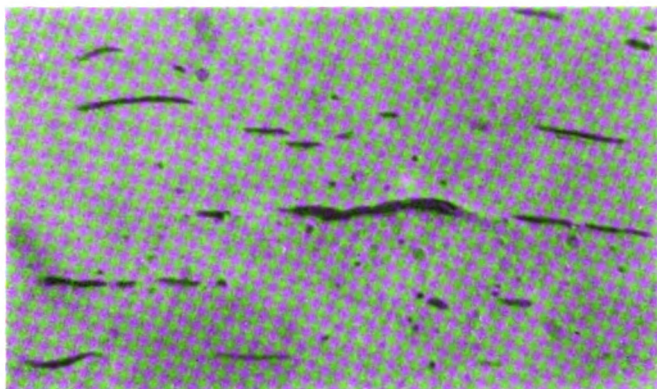


Fig. 166. Silicate Slag Inclusions in Free-Cutting Steel. $\times 100$. Unetched.

growth under sub-critical austenitic transformation temperatures. Molybdenum further possesses properties which favorably influence the case hardening in steel; and, in nitriding, the ever-existing tendency of temper brittleness is entirely obviated owing to the presence of the element.

The addition of a small amount of chromium to molybdenum steel enhances an outstanding quality of ductility, good forming properties, excellent weldability by all prevalent methods, and high toughness and static tensile characteristics. An example of this type of material is the S.A.E. 4130 grade, an alloy of high importance and in extensive use in aircraft structural assemblies, such as tubings, forgings, seat frames, formed shapes for rudder, fittings, brackets, landing gear struts and cylinders, hollow propeller blades, push rods, and other constructional parts such as

bridges, seamless pipes, gas cylinders, etc. One form of this steel has been analyzed as 0.31% carbon, 0.65% manganese, 0.20% silicon, 0.69% chromium, and 0.22% molybdenum. The alloy possesses an excellent strength-weight ratio when adequately heat treated and subsequently quenched and tempered. In the case of airplane engine cylinders, where as high as 40% of the material is removed by machining, an increase in molybdenum range, particularly in a nitriding steel such as Nitralloy G, is required. This is possible because the addition of the element, though it improves the toughness, does not affect the hardness of the material.

Other alloy steels, such as chromium-vanadium steels, tungsten steels, silicon-manganese steels, etc., have excellent static properties, and are usually tempered at higher temperatures than carbon steels, forming complex compounds with iron and carbon more stable than Fe_3C structure. These latter alloying elements together with proper hard facing, in which tungsten-carbide is the prevalent hardening constituent, highest type of hard steel such as used in high-speed tools, rollers, die-casting dies, drawing edges, machine parts, etc., is obtained. The nominal composition of one form of such an alloy may consist of 0.70% carbon, 1.0% vanadium, 4.0% chromium, and 18.0% tungsten.

Within the past few years, due to conditions of stringency arising from conservation of alloying elements such as tin, nickel, or chromium, for war production, S.A.E. alloy steels have given way to some extent to the use of residual alloys in the manufacture of steel. These steels are designated by the prefix "NE" (National Emergency), and develop reasonably high mechanical properties by the addition of small percentages of the alloying elements and by subsequent heat treatment under adequately controlled thermal conditions. By increase in carbon and manganese content and with addition of molybdenum, a reduction of at least 50% in the use of alloy elements vital in other fields of war production at present is curtailed.

CHAPTER XII

RADIOGRAPHY WITH GAMMA RAYS

1. Introduction.—Where there is inspection work with steel too opaque for satisfactory examination by use of x-rays, and where the cost of large capacity x-ray equipment to accommodate such work is of primary concern, the use of gamma rays from radium may be substituted, since the apparatus required for employing radium is very simple. Radium chloride or radium sulphate in small amounts, from 25 milligrams to 800 milligrams in general, may be obtained in hermetically sealed silver pellets, which may be either cylindrical or spherical.

The procedure usually consists of suspending the pellet by means of a string and retaining it at a predetermined distance from the object placed on the usual exposure holder and exposing the film, for instance, at a radium-to-film distance of 15 inches for 2 to 10 hours for steel of a thickness from 1 to 3 inches respectively. As in x-rays, the time of exposure is directly dependent on the intensity (quantity) of radium and varies inversely as the square of the radium-to-film distance.

Because of the simplicity of the gamma ray technique, and of the ease with which the exposures are arranged, the application of radium for radiographing steel castings, welded structures, and parts of irregular dimensions appears to be not only a logical scheme but also attractive from a standpoint of economy and convenience. Furthermore, radium can be advantageously utilized in assemblies and parts such as pipes, pressure vessels, valve seats and flanges, etc., inaccessible by x-ray apparatus. Therefore, radiography by use of gamma rays is not only promising but the method lately has become so popular among practitioners in industrial radiography that gamma ray practice has actually complemented the various phases of x-ray inspection in industry.

2. Radioactive Radiations.—A few months subsequent to the discovery of x-rays (in the fall of 1895), Henri Becquerel announced the phenomenal effect produced by uranium sulphate upon a photographic plate. He also discovered that the radiation from uranium was independent of the latter's state of chemical

combination and of the temperature conditions. The rays further exhibited the power of discharging an electroscope by ionizing the air they traverse. Thus, the property of "*radioactivity*" was assigned to uranium because of its peculiar characteristic of emitting radiations in many ways similar to x-rays but more penetrating than the latter.

The phenomenon was succeeded two years later (1898) by the isolation of radium chloride by Mme. Curie. It was further found that the elements polonium and thorium were also in this category of radioactive substances. But, radium, a disintegration product of uranium, or thorium, exhibited a radioactive intensity more than a million times greater than that of uranium or thorium. Thus, the new radiation was destined to play an important role not only in the treatment of malignant diseases in medicine but also in the detection of flaws in materials of industry by a simple and non-destructive method.

The rays from radioactive substances have the same effect on a photographic plate and on intensifying screens as do x-rays. But, unlike x-rays, there are three types of rays which emanate from a radioactive material. They are α -rays (*alpha rays*), β -rays (*beta rays*), and γ -rays (*gamma rays*). The emanation of these rays can be readily demonstrated by placing a small quantity of, for instance, radium at the bottom of a hole drilled into a block of lead, as illustrated in Fig. 167.

In the figure, a strong magnetic field is sustained at right angles (perpendicular to the plane of the paper) to the vertical aspect of the block. It will be noted that the positively charged α -rays, due to their greater atomic mass are deflected at a larger radius of curvature than the negatively charged β -rays, which are deviated to the opposite side at a smaller radius of curvature. The gamma rays are projected undeviated because of their electromagnetic nature and hence carrying no charges.

It has been shown experimentally that the mass of an alpha particle is 4 with respect to oxygen of atomic mass 16, and that it bears a charge $+2E$, where E is the magnitude of charge of that of an electron. Hence, it may be inferred that alpha particles are nuclei of helium atoms, as when a helium atom becomes doubly ionized it bears a charge $+2E$ and is of a mass 4. Beta particles, on the other hand, are negatively charged electrons believed to be

released by the ionization of "helium-like" structures in the nucleus of the atom.

In the process of nuclear decay, when an alpha particle is shot off from the nucleus of a radioactive material the two corresponding nuclear electrons (beta particles) are left in an unstable state in rotation around the core of the nucleus. The nucleus then tends to acquire a new state of equilibrium, which process results in the expulsion of the two beta particles with the simultaneous emission of two quanta of gamma radiation, each of an energy equal to the corresponding difference of the two energy states of the nucleus.

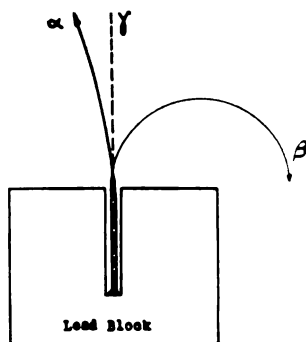


Fig. 167. Illustrating the Separation of Three Types of Rays by Means of a Magnetic Field.

While the penetrating power of the alpha particle is negligibly small (penetrating a few centimeters of air), the beta rays can penetrate a few millimeters of aluminum at an initial velocity approaching that of light. The gamma rays, on the other hand, are capable of penetrating ten inches of steel or over twenty inches of aluminum, possessing a velocity equal to 3×10^{10} centimeters per second, same as that of light.

3. Radium As a Source of Radiation.—Radium is a brilliant white metal, which rapidly tarnishes when in contact with air. It has an atomic weight 226.05, specific gravity 5.0, and a melting point 960°C . It is chiefly obtained from pitchblende in which radium occurs as 1 part in 3×10^6 parts. The disintegration products of uranium and thorium also give rise to radium.

The carnotite sands of Colorado contain about 2% uranium nitrate, which yields radium one part per 3.2×10^6 parts. Richer

uranium sources are found in Canada and in Belgian Congo. Commercially, radium is produced in the form of chloride, bromide, or sulphate, and is chiefly used in the manufacture of self-luminous paints, in the treatment of cancer, and in the detection of flaws in especially heavy industrial metal structures.

We have already seen that the transition of an extranuclear electron from one orbit of higher energy to one of lower energy state results in the emission of an electromagnetic radiation whose frequency is a direct function of the energy difference between the two states. The higher this energy the greater the frequency of the photon thus emitted, and hence the shorter its wavelength (more penetrating radiation). Similarly, the transition of energy between the nuclear energy levels give rise to gamma radiations with wavelengths many times shorter than those emanated from the extranuclear energy levels.

We have also noted that since greater transition energy states in the extranuclear structure gives rise to shorter wavelengths, in like manner the energy of a gamma emanation from the nucleus is dependent on the energy state of the inciting level due to the beta particle. Ellis and Skinner have assigned seven selected energy levels to the nucleus, the transitions among which selections giving rise to fourteen spectral lines hypothetically varified.

Whatever the mechanism of the gamma emanation, we definitely know what effect the radiation produces on matter, and that the emission consists of a mixture of wavelengths ranging from 0.004 to 1.4 angstroms. Since the shortest wavelength that an atom can radiate from the extranuclear structure is of the order of 0.108 angstrom, the remainder of the shorter gamma wavelengths must come from the nucleus as the source. Owing to this heterogeneous character of the gamma rays, the radiation possesses various degrees of penetrative power over a limited spectral range. However, since there is no known practicable method of selective application of these wavelengths, use is made of the average penetrative power of the rays in general.

In contemplating to use a radioactive material for radiography, consideration should be directed to the intensity of the gamma emanation and to its duration. The former property depends upon the number of transformation atoms occurring per second and on the quantity of energy liberated from each atom, whereas

the useful emanation period is dependent on the character of the atom. For instance, uranium of atomic weight 238, through a process of atomic transformation by the successive emission of 3 α -particles and 6 β -rays, disintegrates to a smaller structure of radium of atomic weight 226.

Radium has a half-life of approximately 1580 years, i.e., it takes about 1580 years for a given number of radiant radium atoms to become reduced to one-half. This diminution in the number of these atoms may be quantitatively expressed by an equation as

$$N = N_0 \epsilon^{-kT} \quad (126)$$

where N_0 is the original number of radiant atoms, N is the number of atoms available after a time T , k is the coefficient of transmutation and is characteristic of the transforming atom, and ϵ is the base of the Natural logarithms.

Since the intensity of radium during its decay is a direct function of the number of available atoms at any given time T , the above relation may take the form

$$I = I_0 \epsilon^{-kT} \quad (127)$$

in which, I_0 is the initial intensity of the element, and I is the intensity after a time T .

From the above two equations it becomes at once obvious that the rate of transformation of the atoms is proportional to those untransformed. Therefore, the period in which the activity of the emanation source diminishes to one-half may be computed by equating

$$\frac{1}{2} I_0 = I_0 \epsilon^{-kT} \quad (128)$$

or,

$$\frac{1}{2} = \epsilon^{-kT}$$

from which we obtain

$$\log 1 = \log 2^{-kT}$$

and,

$$T = \log \frac{2}{k}$$

or,

$$T = \frac{0.693}{k} \quad (129)$$

Thus, we see that the rate of the logarithm of the activity of a

radioactive material decreases per given unit time T by the same amount. If the half-period value of a radioactive substance is known, the rate of its decay may be determined by the relation

$$K = \frac{0.693}{T} \quad (130)$$

For example, if the half-period value of radium E is given as 5 days its exponential rate of decay will be given as $k = 0.693/5 = 0.138$ or 13.8% per day. This means that the activity of radium E decreases 13.8% of the activity of the preceding day, so that at the end of the 5th day its emanation intensity is reduced to one-half.

As stated in a previous occasion, the intensity of radioactivity is dependent on the amount of the radioactive material, and is expressed in terms of the equivalent amount of radium. The unit quantity by which the intensity of radium is measured is called the *curie*, named after Mme. Curie, the discoverer of radium. A curie, then, may be defined as the intensity of emanation from one gram of radium in equilibrium with its transformation product (such as with radon, which is an inert gaseous radium emanation having an atomic weight of 222.0). The equivalent strength of one milligram of radium will be expressed as one millicurie. Since the quantity of radium present in a silver pellet employed for industrial radiography is usually expressed in milligrams, its strength in millicurie equivalent may be at once inferred by knowing the exact magnitude of the weight of the element radium and not its salt. For instance, if a certain radium sulphate capsule is said to contain 100 milligrams of radium, the actual weight of radium sulphate is 142.5 milligrams, of which 226.05/322.11th part is radium (i.e., 100 milligrams), as the atomic weight of radium is 226.05 and molecular weight of radium sulphate is 322.11.

The radium sulphate densely packed into the silver pellet for industrial work is an insoluble colorless compound. By spontaneous transformation, radium disintegrates into the radium emanation above referred to as *radon*. Radon is colorless and extremely deleterious to the tissues of the body especially when it is breathed, and hence the hermetic construction of the radium capsule. Such an arrangement further renders the radon emanation in continual

contact with radium. In this manner, radon is replenished as fast as it disintegrates, and once the equilibrium between the emanation of radon and its disintegration is established (which takes about a month after sealing the radium in the pellet) the radiation intensity becomes constant, being a direct function of the quantity of radium present.

In use, the silver pellet is usually enclosed in an ovoid container made of aluminum or steel. This additional capsule protects the silver container (whose wall thickness is of the order of $\frac{1}{2}$ mm) from becoming accidentally damaged during the radiographic manipulation and is not intended in any way to screen off the radiation from the gamma-ray practitioner. Therefore, the handling of radium in the latter capsule should be performed with the same precaution as with radium in the primary silver container. The usual method of handling a radium capsule is by means of a string attached to the upper and lower eyelets on the outer capsule, or, when the latter is made of steel or iron, by using a magnetic handling rod generally furnished with radium enclosed in this type of outer shell.

4. Technique of Gamma-Ray Radiography.—Fundamentally, the scheme employed in gammagraphy is similar to radiography by use of x-rays. In the former method, the focal spot of an x-ray tube is replaced by a radium pellet so designed that the radium contained in it occupies as small a volume as possible, thus tending to produce the effect of a reduced focal spot dimension. Since the radiographic density is a direct function of the amount and hence of the intensity of the radium present, the technique for various exposures may be established with a given quantity of radium by regulating the radium-to-film distance and the time of exposure in accordance with the thickness radiographed.

The penetrating power of gamma rays remains practically the same for all materials of industry when compared with x-rays on identical materials. That is, the mass absorption coefficient of gamma rays for different materials are of the same order as x-rays of the higher voltage range (650 kilovolts or over). Tables and chart forms are prepared giving the absorption coefficients for gamma radiations, and once the absorption value of a certain given metal is established from these forms, it becomes comparatively an

easy matter to determine the equivalent half-value thickness. Indeed, the fraction absorbed by a given material can be readily computed by multiplying its coefficient of absorption by its thickness in mms. The relation may be expressed as

$$\text{Per Cent Absorption} = (\rho \times T)100 \quad (131)$$

$$\text{Per Cent Transmitted} = 100 - (\rho \times T)100 \quad (132)$$

where ρ is the coefficient of absorption, and T is the thickness in millimeters of the material under consideration.

Example:—What will be the fraction of intensity transmitted through a sheet of aluminum 6 centimeters thick and having coefficient of absorption equal to 0.007?

From equation (132), we may write

$$\begin{aligned} \text{Per Cent Transmitted} &= 100 - (0.007 \times 60)100 \\ &= 100 - 42 \\ &= 58 \text{ per cent. } \textit{Ans.} \end{aligned}$$

Since the quantity of radiation from a given capsule can not be varied (unless it is replaced by another capsule), the intensity of the radiation can not be varied. If parts of equal thicknesses are to be gammagraphed, it will be desirable to examine simultaneously as many parts as is practicably possible. On the other hand, with parts having different thicknesses, it will be expedient to make the exposure for various thicknesses either at varying source-to-film distances or with varying exposure intervals. But, in routine inspection work, it is found more practical to expose more than one part at a time even the thicknesses may vary within a wide range. In such a case, it is customary to keep the exposure time constant and to vary the radium-to-film distance in accordance with the thickness of the material. For instance, if four pieces of steel of thicknesses respectively $\frac{1}{2}$ inch, $\frac{3}{4}$ inch, $1\frac{1}{4}$ inch, and $2\frac{1}{4}$ inches are to be radiographed simultaneously with, say, 100-milligrams of radium, the usual scheme calls for a constant exposure interval with varying distances in order to utilize all available radiation time.

By consulting an exposure chart such as given in Table XXI, we find that the shortest time of exposure for $2\frac{1}{4}$ -inch steel block at a practical distance of, for instance, 10 inches is 2.7 hours. Having this last figure as the basis, we explore the horizontal row

of figures across $1\frac{1}{4}$ -inch thickness until we arrive at an exposure value which is the same or nearest to 2.7 hours. Then we follow this column vertically up to the top row which gives the distance values. We find this distance to be 15 inches. Similarly, exploring for $\frac{3}{4}$ -inch, and $\frac{1}{2}$ -inch thicknesses for exposure interval of 2.7 hours, we find respective distance values of 18 inches and 20 inches.

TABLE XXI:—EXPOSURE TIME VALUES FOR GAMMAGRAPHY
OF STEEL WITH 100 MILLIGRAMS OF RADIUM
(TIME IN HOURS).

Thickness in Inches	DISTANCE														
	6"	8"	10"	12"	15"	18"	20"	22"	24"	28"	30"	32"	36"	46"	
$\frac{1}{4}$	2	36	57	80	1 25	1 8	2 24	2 7	3 25	4 35	5 0	5 77	7 25	11 8	
$\frac{1}{2}$	25	44	68	98	1 5	2 2	2 7	3 3	3 9	5 35	6 0	6 9	8 8	14 2	
$\frac{3}{4}$	30	53	83	1 2	1 85	2 7	3 3	4 0	4 75	6 4	7 35	8 4	10 3	17 2	
1	36	65	1 0	1 45	2 2	3 25	4 0	4 8	5 75	7 8	8 9	10 2	13 0	21 0	
$1\frac{1}{4}$	45	78	1 2	1 75	2 7	3 9	4 8	5 8	7 0	9 4	10 8	12 2	15 7	25 5	
$1\frac{1}{2}$	54	95	1 5	2 1	3 25	4 8	5 8	7 2	8 4	11 5	13 1	15 0	19 0	31 0	
$1\frac{3}{4}$	65	1 15	1 8	2 55	4 0	5 8	7 2	8 6	10 2	14 9	15 9	18 1	23 0	37 5	
2	78	1 4	2 15	3 1	4 8	7 0	8 2	10 5	12 5	16 9	19 2	22 0	28 0	46 0	
$2\frac{1}{4}$	95	1 7	2 7	3 75	5 8	8 5	10 5	12 5	15 0	20 3	23 1	26 9	33 7	55 0	
$2\frac{1}{2}$	1 15	2 0	3 15	4 5	7 0	10 2	12 5	15 2	18 0	24 8	28 1	32 2	41 0	66 5	
$2\frac{3}{4}$	1 4	2 5	3 85	5 5	8 5	12 5	15 2	18 5	22 0	30 0	34 0	39 0	49 5	81 0	
3	1 7	3 0	4 7	6 6	10 4	15 0	18 5	22 5	26 5	36 0	40 3	47 5	60 0	97 5	
$3\frac{1}{4}$	2 0	3 6	5 7	8 0	12 5	18 0	22 5	27 0	32 0	44 0	50 0	57 5	72 5	118 0	
$3\frac{1}{2}$	2 5	4 4	6 8	9 75	15 0	22 0	27 0	33 0	39 0	53 5	61 0	70 0	88 0	143 0	
$3\frac{3}{4}$	3 0	5 3	8 3	12 0	18 5	27 0	33 0	40 0	47 0	64 0	73 5	84 0	107 0	173 0	
4	3 6	6 4	10 0	14 3	22 0	32 0	40 0	48 0	57 0	78 0	88 0	102 0	130 0	210 0	
$4\frac{1}{2}$	5 25	9 4	14 8	21 2	32 8	47 0	58 0	70 1	84 0	112 0	130 0	150 0	188 0	308 0	
5	7 7	13 8	21 5	31 0	48 0	69 0	85 1	102 0	122 0	168 0	189 0	220 0	275 0	450 0	

NOTE—This chart applies only to no-screen films. In using other types of films the equivalent exposure time may be computed by consulting Tables X and XI, which give respectively the characteristics of Eastman and Agfa radiographic films.

Therefore, the four steel blocks may be arranged for simultaneous exposure as follows: For the $2\frac{1}{2}$ -inch block the radium-to-film distance is 10 inches, for $1\frac{1}{4}$ -inch thickness the distance is 15 inches, for $\frac{3}{4}$ -inch block it is 18 inches, and for $\frac{1}{2}$ -inch thick-

ness a focus-film distance of 20 inches is used, as illustrated in Fig. 168.

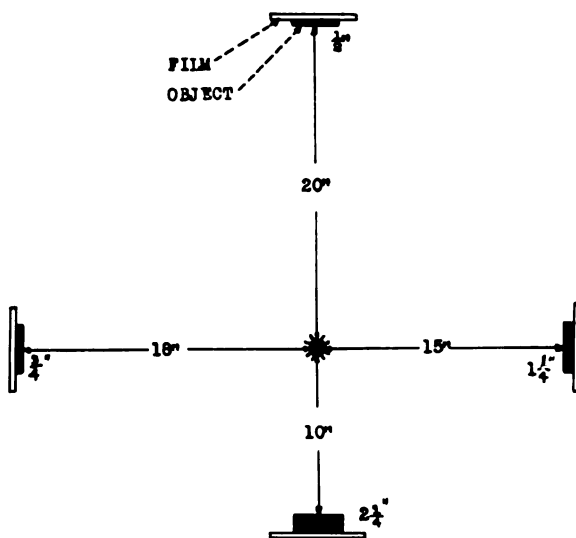


Fig. 168. Illustrating the Simultaneous Gamma-Ray Exposure Technique.

If the quantity of radium is different from that for which the chart is prepared, the time of exposure can be readily corrected for by the following relation:

$$T = \frac{T_o \times G_o}{G} \quad (133)$$

in which, T is the new time of exposure, T_o is the exposure time given in the chart for G_o milligrams of radium, and G is the milligrams of radium by means of which the given part is to be gammagraphed for time T . For instance, the exposure time T required when 100 milligrams of radium is used would be twice as long when using 200 milligrams of radium at the same distance.

Example:—If a steel plate of $3\frac{1}{4}$ -inch thickness requires 32 hours of exposure with 100 milligrams of radium at a distance of 24 inches, how long will it take to gammagraph it with 250 milligrams at the same distance?

According to equation (133), we may write

$$T = \frac{32 \times 100}{250}$$

$$= \frac{3200}{250} = 12.8 \text{ hours. } \textit{Ans.}$$

When it is desired to make an exposure at a distance other than any of those given in Table XXI, the time of exposure may be calculated by applying the *inverse square law*. For example, let us assume that a steel plate measuring $\frac{1}{2}$ inch is to be gamma-graphed at a distance of, for instance, 60 inches. It is desired to know the exposure time at this distance.

By consulting Table XXI, we find that at 30-inch distance the exposure time for $\frac{1}{2}$ -inch steel is 6 hours. But, 30 inches is one-half of 60. Therefore, by doubling the distance ($30 \times 2 = 60$) the time of exposure, of necessity, will be increased four times in accordance with the inverse square law. Hence, the new exposure time at 60 inches will be $6 \times 4 = 24$ hours.

Suppose an exposure for the above thickness ($\frac{1}{2}$ inch) is to be made at 23 inches, (which distance is not included in the table). For an exposure of $\frac{1}{2}$ -inch thickness at twice this distance (i.e., 46 inches), Table XXI gives 14.2 hours. Therefore, at 23-inch distance, the time of exposure will be one-fourth of 14.2, i.e., $\frac{1}{4} \times 14.2 = 3.55$ hours, or 3 hours and 33 minutes.

Let us further assume that the charts available for gamma-ray exposure are made for various thicknesses of steel, and it is desired to gamma-graph, for instance, brass (or, aluminum!). In such a case, it will be found expeditious to convert the thickness value of the brass into steel equivalent by consulting Table VII, or by calculating by use of equation (68). The exposure time for the equivalent thickness, then, may be computed by a reference to Table XXI. Or, in an alternative case, the new exposure time may be found to a close approximation by multiplying the steel equivalent of brass (See Table VII) by the time of exposure for steel of the given thickness.

Example:—A certain brass casting, $1\frac{1}{2}$ inch thick, is to be gamma-graphed at a distance of, for instance, 24 inches. What will be the time of exposure?

The exposure time for $1\frac{1}{2}$ -inch steel gamma-graphed at 24

inches is given as 8.4 hours. The steel equivalent thickness of brass as shown in Table VII is 1.1. Therefore, by multiplying 1.1 by 8.4 we obtain 9.24 hours, which is equal to 9 hours, 14 minutes, and 24 seconds, of which time the last quantity may be ignored.

In the event that exposure charts or tables are not available, the radiographer can establish his own exposure techniques by knowing the distance-time factors of at least one exposure technique relating to a given thickness. He may, then, write the following relation and calculate for any distance or exposure time desired.

$$\text{Gammagraphic Intensity} = \frac{R_m \times T}{D^2} \quad (134)$$

in which, R_m is the quantity of radium in milligrams, T is the exposure time in hours, and D is the radium-film distance given in inches.

For instance, if it requires 7 hours of exposure to gammagraph steel 2 inches in thickness with 100 milligrams of radium at a distance of 18 inches, the exposure time for 24 inches may be computed by equation (134) as follows: For a given thickness of the same material if a gammagraphic intensity A gives an optimum radiographic quality, a second exposure technique B must be so arranged that its resultant numerical value is equal to that of technique A . Hence, the gammagraphic intensity for 2-inch steel at a distance of 24 inches can be equated as

$$\frac{T \times 100}{24^2} = \frac{7 \times 100}{18^2}$$

where T is the exposure time at 24-inch radium-film distance; and, solving for T we obtain

$$\begin{aligned} T &= \frac{7 \times 100 \times 24^2}{100 \times 18^2} \\ &= 12.44 \text{ hours. } Ans. \end{aligned}$$

5. Gammagraphic Alignment.—In gammagraphy, as in x-ray radiography, an important factor of primary consideration is the alignment of the area of interest with respect to the radiation source and the recording surface. This means that the radia-

tion source must be perpendicularly centralized with reference to the center of the object and the exposure field. Parts may be placed either below or above the radium source; and, if desired, they may be arranged surrounding the radium. If objects of irregular dimensions are to be exposed, the radiation intensity may be equalized by placing the radium opposite the thicker sections. In such an event, the time of exposure is determined by averaging the exposure for the thick and thin sections.

Aside from proper alignment of the part, the radium-to-film distance and defect-to-film distance are also important in the attainment of the optimum sharpness of detail. That is, the ratio of d to t (d/t), where d is the focus-film distance and t is the thickness of the section, should be kept as high as can practically be consistent with the exposure time. With small sources of radium, the ratio of d to t may be made relatively smaller. Up to 500 milligrams of radium, the radium pellet may be considered as a point source. Beyond this quantity, the capsule will have comparatively a larger volume, and hence the distance should be accounted for within close limits. The minimum radium-to-film distance as set forth in the U. S. Navy specifications and by other authorities may be summarized as follows:

Milligrams of Radium	1-Inch Steel	3-Inch Steel	4-Inch Steel
25	6	9	15
100	8	10	17
250	10	12	20
500	14	16	23

In general, the optimum gammagraphic conditions will be met when the source-to-film distance is between four to six times the thickness of the heaviest section of the part under consideration.

Though a short radium-to-film distance will result in excessive distortion and impairment of detail, when gross defects in relatively thick sections are examined, the closeness of the radium source to the object produces a magnifying effect of the defect, thus tending to accentuate the latter's presence. In such a case, the shorter distance lends itself to some advantage.

As in x-rays, the farther the source of radium is placed from the film the greater the area that can be exposed to the radiation becomes. That is, as shown in the above table, for 1-inch steel

exposure the minimum distance is given as 6 inches, at which distance an area not larger than 36 square inches (6" x 6") will be successfully gammagraphed. When the distance is raised to 12 inches, the area that can be advantageously exposed will increase to 12" x 12" or to 144 square inches. Thus, it becomes obvious that doubling the distance the exposure area may be increased four times, and tripling the distance the exposure field may be increased to 9 times the original area.

A further factor which should be kept well in mind is the size of the film used. Relative to source-film-distance, the diagonal dimension of the film should not exceed the distance between the film and the radium when relatively flat parts are gammagraphed. With cylindrical objects, the radiation source may be placed inside the cylinder and the latter's entire circumference may be exposed at one time with films affixed on the outside of the cylinder wall. In such an event, the optimum area of the exposure field will have a width equal to the radius and a length three times the diameter (6 times the radius) of the cylinder.

6. Distance In Relation To Focus Size.—In gammagraphy, the size of the radium source simulates the focus of an x-ray tube. Therefore, the radium source should have as small a volume as is practically possible. Up to 500 milligrams of radium, the size of the silver pellet enclosing the radium salt may be considered as a point source. But, in examining minute flaws at close ranges, if the size of the defect is smaller than the size of the radiation source, the defect may entirely escape detection. Hence, in gammagraphing minute cracks, fissures, shrinks, or fine gas porosity, in relatively small thicknesses it will be of considerable advantage if the radium distance is increased but with due regard to the exposure time.

Sharpness of detail will naturally result from a longer radium-to-film distance. But, with thick metals of high density, an increase in distance will necessitate a corresponding increase in the exposure time. An indiscriminately long exposure time, on the other hand, will give rise to an increase in secondary radiations, thus curtailing a reduction in sharpness of image due to prevailing fog and to some extent militating against the advantages thus gained. Therefore, particular attention should be directed to the time of exposure when examining thick castings. It is also found

in practice that undue exposure to gamma radiation produces the effect of "graininess" in the image.

7. Intensifying Screens, Filters, and Penetrameters.—Intensifying screens generally used in gamma-ray radiography consist of metal foils of heavy elements such as lead, lead-antimony, tin, nickel, or the like. The radiation causes a copious emission of electrons from the metal foil, and which electrons affect the emulsion of the film in intimate contact with the screen. This produces an intensifying effect on the film radiated so that the time of exposure may be decreased to three-fourths to one-half that without the use of the screens.

The metal screens further serve to partially eliminate the characteristic radiations incited by the part gammagraphed, thus tending to accentuate the detail sharpness. In such a capacity of use, the metal foils may be considered as filters against long-wave characteristic radiations which are usually given off from thick sections under relatively long exposures.

While calcium tungstate intensifying screens are useful to some extent in reducing the time of exposure, their use in gammagraphy is not recommended in general. The definition obtained by use of a calcium tungstate screen is usually inadequate, and that the exposure reduction advantages offered by it are relatively so small that the use of the screen may be entirely dispensed with.

As in x-ray radiography, sections gammagraphed should bear a penetrameter of appropriate size to indicate the degree of definition obtained as well as to determine the radiographic density. Though a radiograph made with gamma rays does not possess a high detail definition, with discreet use of distance, exposure factors, and metal screens, a sensitivity of 1.5% is not impossible to obtain in routine exposure work. Defect size and depth can be measured by the same methods as applied in x-ray radiography.

8. Absorption and Scattering of Gamma-Rays.—Gamma-rays in passing through metal objects become reduced in intensity owing to their partial absorption and partial scattering by the metal. In this respect, same rules as for x-rays apply except that the scattering in gammagraphy is not of particular annoyance. This is also true with characteristic radiation incited by thick metal sections. Because no serious fogging is consequenced by these secondary radiations, it does not become necessary to shield

the radiographic film by use of lead plates or copper powder. However, it is recommended that the time of exposure be kept as low as is practicably possible in order to avoid what little fogging due to secondary rays may result in any exposure.

9. Processing of the Gamma-graphic Film.—The processing of the gamma-graphic film is closely allied to the procedure used in x-ray work. However, the gamma-graphic film may be developed in a developing bath containing 20 milligrams of potassium iodide per liter of the solution. The addition of the salt restrains the formation of chemical fog, permitting a longer development time (about twice the normal development time) if such be regarded as of any consequence.

When gamma-graphing is executed with proper exposure technique the film may be developed in a reasonably fresh x-ray developer for full development interval as for an x-ray film. Such an interval should be in accord with pertinent development time interval charts usually furnished by the manufacturer of the processing chemicals.

The fixing, washing, and temperature conditions strictly follow the procedure as for x-ray films. The reader, therefore, is directed to refer to discussions relating to x-ray film processing included in pertinent sections of this book.

10. Viewing and Interpreting Gamma-graphs.—The interpretative value of a gamma-graph is materially dependent on the quality of illumination. As in x-rays, the light from the illuminator must be of a character approximating daylight. Fluorescent illumination as well as argon-filled blue bulbs of high intensity may be employed for good advantage. Since the conditions for illumination of gamma-graphic films are same as for x-ray radiographs, all particulars regarding the subject may be studied under pertinent headings for x-ray films.

Same scrutiny as for x-ray radiographs should be given to gamma-graphs in that the defects revealed by use of radium are of identical photographic character as when they are radiographed by x-rays. An outstanding difference is the comparatively high latitude of density gradations obtained in a gamma-graph in contrasting relation to x-ray radiographs. Furthermore, gamma-graph of a part will present an image of greater unsharpness than an x-ray radiograph would under identical physical conditions.

All commonly encountered defects as listed in this book under discussions relative to the detection and interpretation of defects revealed by x-rays should be consulted for acquiring a compre-

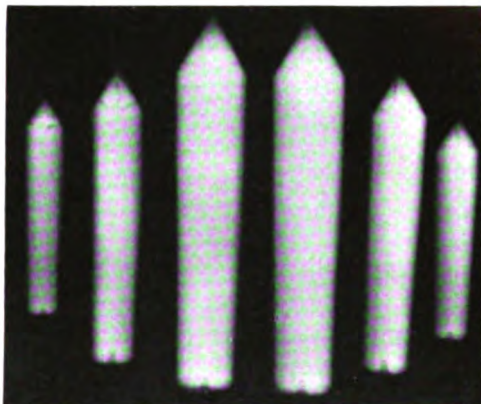


Fig. 169. Gammagraph of Lathe Centers Showing Excess Voids Due to Trapped Gas.

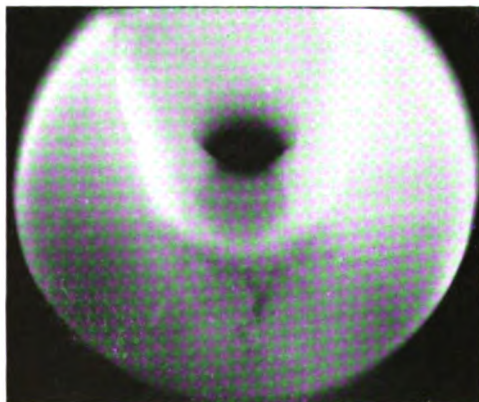


Fig. 170. Gammagraph of Bronze Casting with Excessive Macrosink.

hensive knowledge for interpreting similar defects revealed in a gammagraph. With this in view, the author has abstained from repeating the discussion on the subject in this chapter. The gammagraphs illustrated in Figs. 169 and 170 are intended only to

exemplify with reserve the character and quality of definition that can be obtained by use of radium.

11. Safety Precautions in the Use of Radium in Industry.—

In handling radium in gammagraphy, the radiographer at all times must keep in mind that radium is continually active and is constantly giving off emanations injurious to human body when exposed indiscriminately. Therefore, every precaution should be taken by the operator to retain a reasonably long distance from the radium and for a minimum of time. The latter two factors—namely, distance, and time—are the only protections that the gammagrapher can rely upon with safety when safety rules relating to these are strictly observed.

Depending on the quantity of radium handled in gammagraphic work, the distance and the time of exposure of the body to the radiation vary in proportion. That is, with greater amounts of radium the distance at which the manipulation is executed should be increased or the time of exposure shortened in accordance. Lead and other heavy metals when interposed between the radiation source and the operator may reduce the danger of exposure to some extent but such should not be considered as an immunity against the potency of the radiation. The recommended safe working distances as given in the National Bureau of Standards Handbook H23 are listed in Table XXII.

TABLE XXII:—SAFE WORKING DISTANCES FOR
VARIOUS QUANTITIES OF RADIUM.

Milligram-Hours Daily Exposure	Safe Distances (In Feet)
100	3
200	4
400	6
800	8
1600	11
3200	15

As stated in a previous section, the best protection against undue radiation is to handle the radium with long magnetic rods (several feet long) or by means of long strings attached to either end of the protective capsule around the radium pellet. It will be also advisable to always make preparations for the exposure previous

to the removal of the radium from the lead-lined box (which should have a wall thickness between $2\frac{1}{2}$ to 6 inches, depending on the quantity of radium). Great care should be exercised that the pellet enclosing the radium salt is not crushed or broken accidentally, as the resultant release of radon gas is fatally dangerous when breathed.

As in x-rays, the amount of radiation from radium that can safely be absorbed without producing ill effects in the human body varies with different individuals. An average tolerance dose based on the consideration for producing an erythema reaction is given as 0.1 roentgen per day. For further protection of the operator, the intensity of the radiation from the radium source at a given distance where the operator executes his usual manipulations during exposures may be measured by means of a Minometer or an R-meter to establish a safe permissible distance in behalf of the gammagrapher and those who are assisting in the exposure procedures.

CHAPTER XIII

MAGNETIC INSPECTION OF MATERIALS

Magnetism is one of the earliest physical discoveries ever made in pure science. The effect has been first noted in lodestone (a crude ore of iron having a chemical formula of $\text{FeO} \cdot \text{Fe}_2\text{O}_3$) which possesses the peculiar property of attracting pieces of iron when brought near it. Furthermore, by rubbing iron with lodestone the former acquires the power of attracting particles of iron to itself. Such a property is known as *magnetism*, and metals which exhibit this characteristic are called *magnetic substances*.

When a metal is magnetized it acquires two magnetic poles which may be considered respectively as the "inlet" and the "outlet" of the magnetic force which encircles the metal by way of the poles. This encirclement of the magnetic force executes a definite and more or less continuous pattern extending from the interior to the exterior of the metal in the normal state. When this pattern is disturbed as by a discontinuity in the metal, by abrupt changes in the crystal boundary structure, segregation, inclusions, or by plastic deformation of the metal and causing a notable change in the permeability, there is a tendency of the magnetic force to deviate from its normal course in the metal and appear to some extent on the surface adjacent the origin of disturbance. It is this latter phenomenon which makes the detection of flaws in iron or steel possible. The principle which employs magnetism to reveal surface or sub-surface flaws in iron or steel parts is known as *magnetic inspection*, or *magnetic analysis*.

1. Magnetic Substances.—Magnetism naturally occurs in iron and to some extent in metals such as nickel, and cobalt. Some metals while in their elemental state are practically non-magnetic become highly magnetized when alloyed with iron and subjected to a suitable magnetizing influence. An example of this is aluminum in the magnetic alloy commercially known as Alnico consisting of 12 per cent aluminum, 20 per cent nickel, 5 per cent cobalt, and aluminum for the balance. Powerful magnets are generally made of cobalt-steel, while tungsten-steel and chromium-steel combinations are also frequently employed for this purpose.

These alloys possess high magnetic properties, and, therefore, are known as ferromagnetic substances.

Magnetic substances are magnetized either permanently or temporarily under a magnetic influence. Those that are magnetized permanently are made of hardened steel or of a combination of steel and either one of the elements tungsten, chromium, nickel, cobalt, or aluminum. A *permanent magnet* is one which retains its magnetism for a considerably long period after the magnetizing force is removed. A horse-shoe type magnet and a bar magnet are examples of permanent magnets. *Temporary magnets* are those substances which become easily magnetized but do not retain their magnetism after the magnetizing force is removed. That is, the latter type of magnets (electromagnets) behave as magnets as long as they are under the influence of a magnetizing field. When this field is removed they lose their magnetism. Temporary magnets are usually made of laminated sheets of soft iron, which are extensively used in the manufacture of cores for electromagnets, transformers, generators or motors, and various other types of induction apparatus.

The magnetic effect is found to act through most substances. Unlike electricity, there is not any known magnetic insulator. Small pieces of iron placed on a thick plate of glass or on a cardboard will follow the path of a magnet moved back and forth underneath the plate. A partial screening of the magnetic effect is possible if the glass plate mentioned above is replaced by a sheet of iron, which spreads the magnetic force axially in its interior.

2. The Magnetic Poles.—The Earth is considered as the largest magnet ever known. It has two *magnetic poles*—a *north pole*, which is near the south geographical pole, and a *south pole*, which occurs in the neighborhood of the north geographical pole. When a bar magnet is so suspended in air by means of a fine fiber that it can swing freely about its vertical axis, the magnet will orient itself in approximately north and south directions. The end of the magnet pointing to the North is called the north-seeking pole, or simply the north pole, and the opposite end which points to the south geographical pole of the Earth is known as the south pole of the magnet. Such a phenomenon of the magnet aligning itself in the Earth's magnetic field is utilized in the con-

struction of instruments for directional indication in both aerial and marine navigations, and frequently on vehicles travelling on land.

The poles of a given magnet are of equal strength but of opposite polarities. The individual north or south poles never exist by themselves. Whenever there is a north pole at one end of a piece of magnetized iron there is always a corresponding north pole at the other end. Cutting the magnet into two does not result in the separation of the two poles, but each half becomes a complete magnet having a north pole and south pole of equal strength. A circularly magnetized part does not have any magnetic pole.

If the north poles (or south poles) of two magnets are brought together, they repel each other. But, when the north pole of one magnet occurs near the south pole of another magnet, the two magnets attract each other. Hence, *like magnetic poles repel and unlike poles attract*.

3. The Elemental Theory of Magnetic Phenomenon.—In a magnetized piece of metal each molecule is a complete magnet in itself. Such an elemental magnet is associated with the circular motion of the planetary electrons about the nucleus, setting up in space a disturbance recognized externally as magnetism. Indeed, in a bar of magnetized iron, the orbital planes of the revolving planetary electrons in a row of atoms arranged parallel to the long axis of the bar are so oriented that the magnetic effect of each atom is added to the next one in the row, creating a line of disturbance externally behaving as if radiated from a point on the north pole of the magnet, projected in an arc into infinity, and finally focused perpendicularly to a point on the south pole joining the axes of the two poles. Such a disturbance due to the magnetic force is commonly known as a *line of force*.

Electrons revolving in the atomic orbits produce effects analogous to electric currents flowing in conductors having the identical geometrical dimensions as those of the orbits. That is, a moving current in a conductor creates a magnetic field about it. An electron in revolution in an atomic orbit, therefore, will characterize a current in a wire loop having the same diameter as the electronic orbit, and the magnetic field intensity produced within the loop will constitute the strength of an elementary magnet. Hence, in the atoms of a given magnetic substance, orienting the

direction of motion of all such electron systems consistently in the same phase so that all the electrons participating in the formation of these minute magnets will revolve in the same direction produces a magnet. Obviously then, in an unmagnetized piece of iron bar the orbital motions of the different electron systems have haphazard directions, and, thus, the magnetic effect due to them is nullified inter-orbitally.

From the foregoing it will be apparent that an electron rotating in the orbit of an atom possesses an angular momentum, which is an attribute of magnetism as current-magnetic field is what to a moving electric charge. The electron may revolve in, for instance, n th orbit in either direction, the direction of revolution affecting only the positions of the north and south poles of the elementary magnet. Consequently, the component of the magnetic moment associated with an atom in orientation in the magnetic field will amount to one *magneton*, which is the polar strength of an elementary magnet, and is numerically equal to 9.218×10^{-21} erg per gauss.

4. Magnetic Field; Flux Density.—We have already noted that the unidirectional alignment of all like polar planes of the elementary magnets in a magnetic substance will produce a magnet. The space confining the magnetic disturbance incited by the moving electric field due to electrons associated with the occurrence of elementary magnets is usually referred to as the *field of the magnet*.

Around a magnetized bar of iron, the magnetic field is more intense at the poles than at the middle of the magnet. The field starts from the north pole, diverges in a closed path about the entire length of the magnet, and finally converges perpendicularly on the surface of the south pole. This field may exist about the entire axial length and the peripherum of a coil of wire forming a helix and carrying a current. The direction of the magnetic force may be detected by means of a magnetic compass; and, it will be noted that when a bar of hardened iron or steel is inserted into the coil while carrying current, the bar will become longitudinally magnetized. When the bar is used as a conductor and an electric current is made to traverse parallel to its long axis, the bar becomes circularly magnetized.

The strength of the magnetic field is known as the *magnetic*

intensity. A *unit magnetic intensity* is the strength of a unit north pole of a magnet placed 1 cm from another unit north pole and repelled with a force of one *dyne*. The force F in dynes on a unit magnetic pole placed in a magnetic field R of a magnet having a pole strength h may be given as

$$F = Rh \quad (136)$$

and,
$$R = \frac{F}{h_1} = \frac{h_2}{\mu d^2} \quad (137)$$

where, h_1 and h_2 are the pole strengths of the respective magnets, μ is the permeability of the medium between the magnetic poles separated by a distance of d centimeters.

Since the permeability of a non-magnetic medium such as air is unity, the force between the two magnetic poles may be expressed as

$$F = \pm \frac{h_1 h_2}{d^2} \quad (138)$$

in which, the plus and minus signs before the term on the right-hand side of the equation denote that the force between the poles may be respectively either one of repulsion or attraction.

It has been already stated that when a group of elementary magnets are aligned in a row along the entire axial length of a bar of magnet, the magnetic disturbance occurring external to the magnet behaves as if originated from a point source on the north magnetic pole, radiated in an arc, and contracted back to the corresponding point on the south pole of the magnet. For purposes of convenience in discussion, this disturbance is referred to as a *line of force*, also known as a *maxwell*. Thus, the strength of a given magnet may be expressed by the number of lines of force per unit cross-sectional area of one of its pole faces. The total lines of force issuing from a given magnetic pole face is called the *magnetic flux*, and the number of lines of force per unit area in a plane at right angles to the magnetic field is called the *flux density* at that region. The unit field strength or the flux density is called the *gauss*. The flux per centimeter is known as the *gilbert*.

To further elucidate the above magnetic relations, if a magnet

has 25,000 lines of force per square centimeter of its pole face of an area of 4 square centimeters, the total magnetic flux \emptyset may be given as

$$\emptyset = BA \quad (139)$$

or,
$$B = \frac{\emptyset}{A} \quad (140)$$

in which, B is the flux density in gausses, and A is the pole face area in square centimeters.

In considering an electromagnet of L centimeters long and consisting of N turns of wire carrying a current of I amperes, the flux density may be given as

$$B = \frac{4\pi NI\mu}{10L} \quad (141)$$

and, the total flux will be

$$\emptyset = BA = \frac{4\pi NI\mu A}{10L} \quad (142)$$

where, A is the cross-sectional area of the solenoid in square centimeters, and the product NI is usually termed as the *ampere-turns*.

5. The Principle of Magnetic Inspection.—The principle of magnetic inspection of materials to locate flaws or discontinuities consists of magnetizing the part under examination by means of a suitable magnetizing field, followed by the application of a magnetic powder such as iron dust or magnetic iron oxide upon the surface of the metal, and interpreting the patterns thus delineated by the magnetic powder. Any discontinuity in the structure of the material will cause an abrupt change in the magnetic field, giving rise to a *leakage field*. The latter field, if emerges to the surface of the metal, will attract fine particles of the magnetic powder at exactly the same region where the change in the magnetic field due to various anomalies occurs. Such a scheme is commercially identified as *magnaflux inspection*.

The magnetic powder may be applied either dry or wet. The dry method consists of dusting the powder usually after the part is magnetized, whereas in wet method the part may be coated with

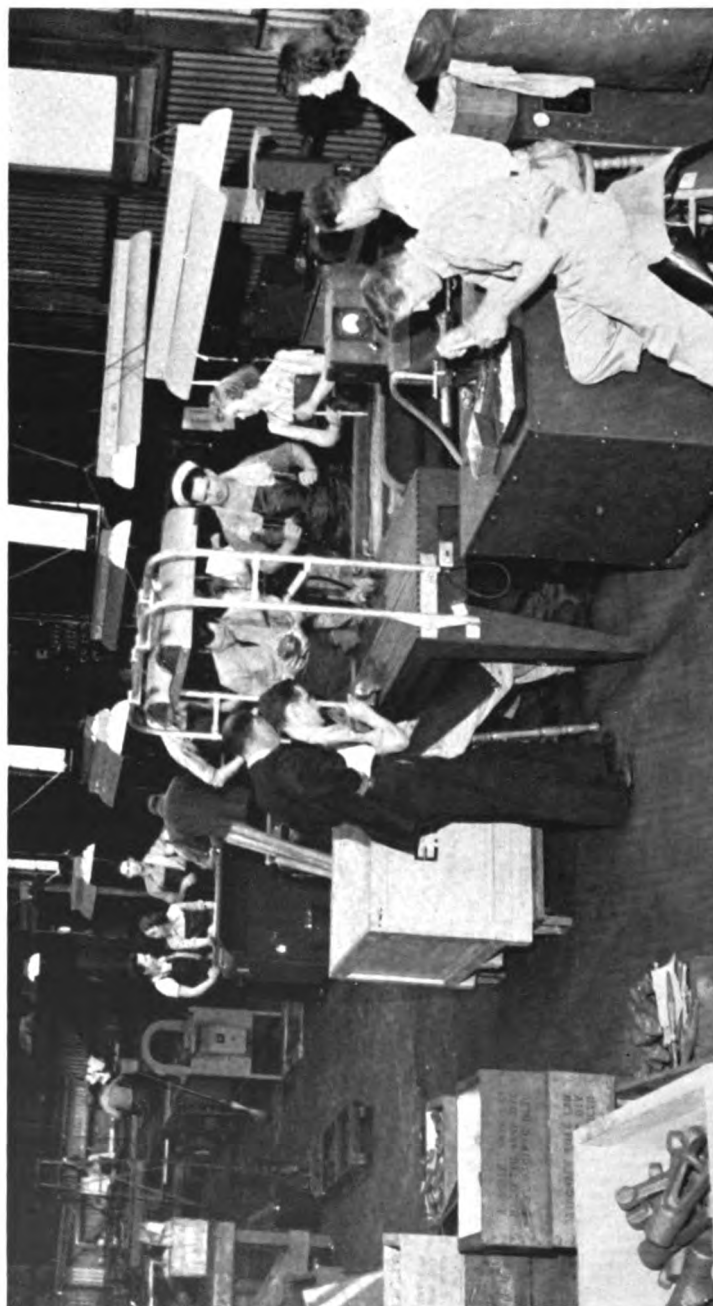


Plate XIV. Various Types of Magnetic Inspection Units Shown In Full Operation. *Courtesy Aircraft X-Ray Labs.*

a liquid magnetic medium either during the magnetization of the metal or after the magnetizing force is removed. In either case, it should be noted that the greater the retentivity (capacity to retain magnetism) of the part magnetized the more accentuated will become the tracks of the leakage fields indicating the flaws in the metal.

The magnetic powder is obtainable in two colors—black, and red. Both are identical in particle size and in magnetic characteristics, the choice of use depending on which color is deemed to give the greatest contrast under the illumination used during the inspection.

Previous to use, the powder is made into a uniform suspension by mixing 1 to 2 ounces of the powder with each gallon of a light oil such as "Base Oil C" or "Bayol D," manufactured by the Standard Oil Company, or "Ultrasene" sold by the Atlantic Refining Company, the magnetic powder content of the suspension depending on the requirement of the magnetic analysis.

The amount of current required to magnetize a given part depends on the size and character of the material. For instance, if a bolt of $\frac{3}{4}$ -inch in diameter is to be inspected, the current may be set to several hundred amperes, whereas with bolts of 1 to 2 inches (or greater) in diameter several thousand amperes are used. This quantity is restricted by the heating effect produced by the passage of the current through the material (as a high current passed through an inspection part of small diameter may burn the metal) and to some extent it is dependent on the magnitude of contrast pattern desired on the surface of the part examined. The interval of current flow for each inspection "shot" is accurately pre-set at from $\frac{1}{5}$ to $\frac{1}{2}$ second.

Subsequent to magnetization and impregnation of the part with the magnetic medium it is examined in proper illumination and then demagnetized under the influence of an alternating current. A high magnetic flux furnished by a large helix carrying a current of 50 to 100 amperes at 115 to 230 volts at either 50 or 60 cycles is usually used for this procedure. This latter operation is of necessity in order to avoid the annoyance due to residual magnetism of the magnafluxed parts when used near assemblies such as electric indicating instruments, and further to reduce the tendency of wear in a contiguous part such as steel bearings or

the like. However, a complete demagnetization is not practicably possible, but in practice it is found that the lower the frequency of the demagnetizing current the higher the penetration of the magnetic flux and hence the more complete becomes the demagnetization. Most magnetic parts generally lose their magnetism upon heating to a temperature known as Curie point, which is about 745 degrees for iron and steel.

All parts that are magnetically inspected are finally cleaned by immersion in a cleaning fluid such as trichlorethylene. The latter, in general, is used boiling at about 87°C so that when the part is removed, it becomes dry in a few seconds due to its own heat. Some of the inspection parts frequently require a coating of oil after the cleaning operation to preserve them from atmospheric attack.

6. Types of Defects Detected by Magnetic Analysis.—In the examination of parts by magnetic flux, careful consideration should first be directed to the character, shape, and size of the material. That is, the material under inspection should possess the property of becoming magnetized under a suitable magnetizing field; and, it should be of such a shape and size that adequate magnetization operations can be performed on it. Since, when a substance is not properly magnetized no true interpretation pattern can be revealed on the surface, thus defeating the purpose of the magnetization procedure. Hence, previous to inspection, the part under inspection should be adequately magnetized by the application of the proper amount of magnetizing current and coated with a suitable medium of magnetic impregnant. Under these conditions, the inspection patterns lend themselves to maximum interpretative value.

The usual types of defects that are revealed by magnetic analysis are those that occur on or near the surface of the specimen examined. It is also possible to detect sub-surface flaws which preferably extend at right angles to the magnetization and are not deeply seated in the metal. For instance, if the defect (whether it is on the surface or under the surface) occurs parallel to the field of magnetization, or if it occurs at such a depth from the surface that no leakage field can be detected on the surface of the metal, the examination becomes an utter failure, and, therefore, the

scheme should be supervised by either x-ray or gamma-ray radiography.

An approximate estimate of the distance below the surface at which a defect can produce an external indication by the application of magnetic principles may be given as $d/D = 1/5$, where d is the depth of the defect from the surface, and D is the distance between the center of the part and its surface. This latter ratio bears the provision that the specimen under interest is fully magnetized and that its angularity is approximately 90 degrees to the magnetization.

Another factor of primary importance is the application of the proper amount of magnetizing current in the detection of a defect which is located in a depth within the above-given defect-to-center ratio range. A defect located near the surface will scarcely be made noticeable by the magnetizing medium when the part under investigation is magnetized by an insufficient amount of current. As will be noted by equation (141), the magnetic flux density B is directly controlled by the magnetizing current I (since all other factors remain constant in a given magnetizing apparatus); and, therefore, the greater the value of the current within other physical limits (governed by the capacity of the generator, size of the magnetizing coil, size of the specimen when carrying current for circular magnetization, etc.) the contrast pattern formed by the magnetic powder will increase. Hence, discretion must be exercised in the selection of the current value as well as the magnetization plane of the specimen which will effect the maximum flux density associated with the existing discontinuity.

Of equally great importance is the character of the material examined in that, in some types of steels, such as manganese steels, and certain stainless steels (such as that containing 18% chromium and 8% nickel type) the development of magnetism is practically impossible. These latter steels especially when in austenitic state possess structures mostly consisting of gamma phase and hence are non-magnetic. The application of the magnetic test, then, to these types of steels will produce no useful results. Such is also true with materials having variations in thermal treatment with consequent inadequacy of permeability.

The types of defects that can be located by the magnetic method are cracks due to thermal treatment, quenching, and machining;

fatigue cracks, inclusions, shrinkage fissures, porosity, gas cavities, laminations, and forging laps. Of these, the first three and sometimes laminations occur superficially, whereas voids due to shrinkage, porosity, blow holes, or inclusions usually occur internally to the metal. Some of these imperfections are a result of improper foundry procedures while others are due to improper physical and mechanical operations during the formation of the product.

If imperfections, such as cracks, inclusions, blow holes, or porosity, which are due mostly to improper foundry procedures, have occurred in a casting, their recurrence can be prevented to an important degree by changing the design of the product, or by modifying the molding procedure as by use of adequate risers, suitably located chills, and above all by use of proper pouring temperature of the metal, which has been previously well fluxed to exclude most of the slag and other oxidation products. If the material is formed by forging or rolling, consideration should be given to the chemical composition of the material by first determining whether or not the metal can be heat treated. The observation of this latter condition is important, as when the metal is not in a heat treatable condition (such as in the case of X1112 steel) due to the carbon and inclusion content of the material, adverse results such as cracks and laminations will come into predominance. These will be further accentuated if the material further undergoes quenching, stamping, or machining operations.

Forging laps, laminations, and inclusions lying parallel to rolling may produce magnetic indications which are at times difficult to differentiate one from the other. In such a case, a pre-knowledge of the character of the material and of its forming operations will greatly aid in arriving at a conclusion in their discrimination.

Seams consisting of non-metallic inclusions, elongated cracks, cold shuts, or of non-fusion zones as in welds, are determined by the characteristic linear patterns produced in the suspected regions. Their sizes vary from a fraction of a millimeter to the full length of the sections in which these anomalies have been revealed by the magnetic medium. In some types of alloy steels, such as chrome-molybdenum type, it sometimes becomes somewhat difficult to adequately detect and localize the seam owing to the interference of the magnetic permeability of the section by the presence of the flaw. In such cases, a supplementary test by micrographic

analysis is helpful if destructive tests can be afforded.

In general, magnetic examination may be applied to various automotive steel parts, such as crank shafts, piston rods, axles, gears, etc., to numerous parts used in aircraft engines and locomotive engines, train and trolley rails, pressure vessels, pipes, drums, and various other steel parts which require rigid inspection owing to their ultimate importance from the standpoints of public safety and economy of time and labor.

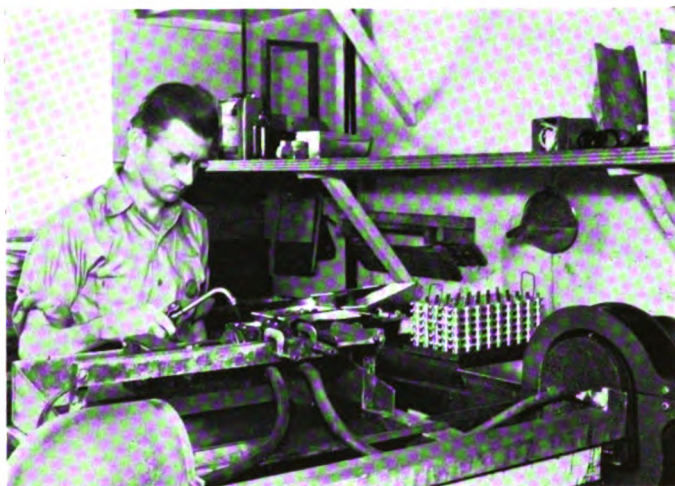


Fig. 171. Illustrating the Use of Continuous Method In Preparing the Specimen for Inspection.

It has been noted in the beginning of this section that in order to locate a defect in a magnetizable material there should first be set up a leakage field. Unfortunately, all indications due to leakage fields are not always representative of discontinuities in the metal. False indications as a result of the magnetic medium clinging to the surface of the part which has come in contact with a magnet as by rubbing against it, cold working, abrupt change of a part from a thick to thin section, abrupt change in angularity of the section, hard spots due to accidental hammering or exertion of pressure against the metal, and due to boundaries of grain structures of especially heat treated forgings, all contribute to the occurrence of false indications which generally bear no reflection

on the quality of the material. Other false indications may arise from surface scratches, machine and stamping marks, and dirt especially when dry powder is used.

In any defect revealed by means of magnetic analysis, the greatest importance resides in the evaluating the character and seriousness of the defect. A slight indication occurring on the surface as a result of the application of an insufficient magnetizing current may prove to be very serious when the part is adequately magnetized by proper quantity of current. In this connection, the importance of the operator's ability and previous training to aid him in determining the proper amount of current to be employed, and in arriving at accurate decisions can not be overlooked, as the disposition of thousands of parts that are daily inspected will solely depend on the operator's prudence and his accurate interpretation of the patterns delineated. Hence, the necessity of selecting a well-trained inspection personnel which can exercise sound judgment in the diagnosis of the magnetic indications can not be over-emphasized.

7. Types of Apparatus Used, and Methods of Inspection.—There are on the market a number of types of magnetic inspection apparatus. These may be classified according to the specific purpose for which they are designed to serve or according to the type of output current which may be either a direct current or an alternating current. When the latter type of classification is considered, a direct current method is used in general when it is desirable to obtain indications at high induction values, and when deep seated defects in materials having relatively large cross-sectional dimensions are sought. The alternating current method becomes valuable from the standpoint of sensitivity, uniformity of analysis of parts which are of uniform cross sections, and economy of use. In the latter scheme, the part usually forms the core of the induction system.

One of the most popular and most widely used apparatus for magnetic inspection is the AN Magnaflux Unit shown in Fig. 172. This unit is energized by direct current furnished from wet storage batteries, and it provides means for magnetizing the inspection parts both longitudinally and circularly. It has a built-in electric pump which constantly agitates the magnetic suspension medium and causes it to continually flow over the surface of the part dur-

ing magnetization. In view of this latter procedure, the scheme is generally referred to as *wet* or *continuous method*.

Located on the top side of the apparatus are two contact heads which serve as the terminals of the high-current circuit furnishing power to magnetize the part circularly. There is also a magnetic coil (shown, in the figure, between the two heads) consisting relatively of a few turns of wire. This coil produces a longitudinal magnetism when the part is inserted into it when energized. The magnetizing current is accurately adjusted by means of a rheostat

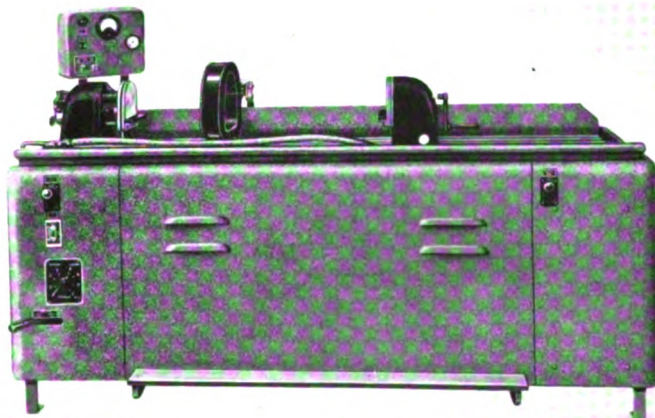


Fig. 172. The AN Magnaflux Inspection Unit.

control and indicated on the ammeter located on a suitable panel on the upper left end of the machine.

The current to the unit is supplied from a usual alternating current line. It is led to a series of tungar rectifiers (4 to 10 bulbs, depending on the capacity of the apparatus), each capable of furnishing a maximum of 5 amperes to each battery. Generally, these bulbs are in constant operation to retain the batteries fully charged practically at all times.

In operation, the part to be inspected (which is previously cleaned of excessive oil and dirt, if any), for instance, by use of circular magnetization, is placed between the two contact heads and securely clamped (by air pressure) so that good contact between the surfaces is established. A required amount of current

is passed through the part while the magnetic medium is continuously flowing over it.

The current flows for about $1/5$ to $1/2$ second, which interval is considered to be sufficient to magnetize any given part. The part, then, is removed by loosening the contact heads, and inspected in a suitable illumination. After inspection, the specimen is demagnetized before shipment is made.

For faster production inspection of comparatively small parts, a

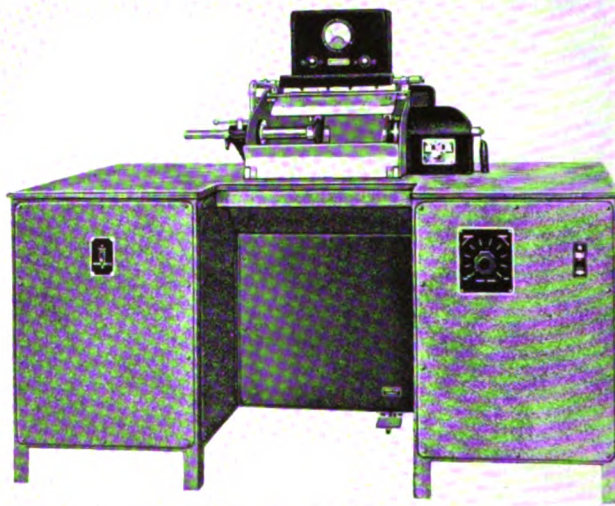


Fig. 173. SMQ Magnaflux Rapid Inspection Unit.

unit known as SMQ Magnaflux Unit is generally employed. The apparatus, shown in Fig. 173, is designed for rapid inspection of small parts up to 12 inches long. The energizing current is furnished rectified from a three-phase alternating current source. Both surface and sub-surface defects may be located by means of this unit.

The circulating system for the magnetic suspension fluid used in SMQ unit is so designed that the liquid may be automatically flowed over the inspection part for a predetermined time by use of a small foot pedal. When in full operation, the hourly inspection capacity of the apparatus is between 400 to 600 small parts.

Another inspection apparatus which lends itself to great use in rapid production inspection is the type designated as SCQ Magnaflux Unit. The device, shown in Fig. 174, is a complete inspection machine consisting of magnetizing, inspection, and demagnetizing systems, all included in one unit. It is particularly adapted to the inspection of small bolts and studs for transverse defects.



Fig. 174. SCQ Combination Inspection and Demagnetizing Magneflux Unit.

In the left-hand section of the apparatus, there is a tank containing the magnetic fluid which is kept constantly agitated by means of an electric pump. In the middle section, there is an inspection station furnishing ample light for adequate examination of the materials. The supply current is usually taken from a 60-cycle 110-volt alternating current circuit. This current is

rectified before it is applied to the energizing coil which surrounds the tank containing the magnetic fluid.

Near the upper rim of the tank and above the magnetizing coil is located a source of light which constantly illuminates a photoelectric cell oppositely mounted in the system. When parts are dipped into the magnetic suspension in the tank, the light beam is interrupted, and the photoelectric circuit instantly closes a relay



Fig. 175. The KQ-1 Portable Magnaflux Unit.

which energizes the magnetic coil for a predetermined interval of time.

The magnetized part is inspected under the inspection station illuminated by fluorescent light, and then immersed into the rinsing bath at the right-hand section of the machine. In this tank, the part is both rinsed and demagnetized.

A magnetic inspection apparatus of unique purpose is the portable type called KQ-1 Magnaflux Unit. It is designed par-

ticularly for weld inspection, and is energized from a three-phase AC line at either 220 or 440 volts.

The rectified current is suitable for the inspection of castings, forgings, rails, gun mounts, weld seams along steel vessels, drums, and, in general, practically all types of welds, because of its affording a deep penetration. The current capacity ranges from 600 to 1200 amperes at low voltage, avoiding arcing or burning of the metal at contact points. This current is led to the section under examination by means of heavy and flexible cables ending in suitable electrodes, which are placed on either side of the section to be examined and are energized by an adequate quantity of current during inspection.

Subsequent to the magnetization procedure, the magnetic powder is dusted over the section, and then blown off. The clinging particles, if any, indicate the location and the extent of the defect in or under the surface of the metal.

While it is not necessary to demagnetize every part after inspection, it is essential that all parts retaining an appreciable degree of magnetism after inspection be subjected to this procedure. Some parts, for instance, having low retentivity, or having been magnetized both circularly and longitudinally, will lose most of their magnetism sometime after inspection. Therefore, such parts need not be demagnetized.

There are several methods of demagnetization. Of these, the one employing a solenoid energized by an alternating current at 50 or 60 cycles is in most general use. Some of the machines of this type employ a 25-cycle alternating current, which produces deeper penetration. The important factor to keep in mind in this operation is to always turn on the current to the demagnetizing coil previous to passing the part through it. Furthermore, the part should be withdrawn from the coil to a distance where no attraction by the coil can be felt by the operator.

The parts may be placed on a movable platform fitted with rollers so that it can be pulled easily through the coil at a uniform rate. The uniformity of movement of the part is desirable in order to effect a gradual but reasonably complete demagnetization. A typical demagnetizer of this description and adapted to the demagnetization of various sizes of inspection parts as well as

large propeller hubs and aircraft engine crankcases is shown in Fig. 176.

When parts are too large to be passed through the demagnetizer coil, they can be brought near it and withdrawn at a uniform speed, or they may be rotated while in the influence of the magnetic field. One other method is to insert into the solenoid the middle section of a heavy insulated cable coiled into a number of turns, and by extending one end to the part to be demag-



Fig. 176. SB-2814 Magnaflux Demagnetizer.

netized and winding a few turns around the section to join the ends of the cable to make an electrical contact. When the demagnetizer is energized, a large current is induced in the coil of the cable. This current flowing in the winding placed around the section under examination produces a magnetic field whose intensity fluctuates with the frequency of the demagnetizer current. This causes a longitudinal demagnetization in the section, as the coiled cable is gradually pulled out of the demagnetizer coil, which procedure produces the effect of a gradually attenuating magnetic field around the section under interest.

8. Magnaglo, and Zyglo Inspections.—Recently, a new type of inspection method, developed by the Magnaflux Corporation, employs a fluorescent liquid medium, which, when applied to the surface of the magnetized part, produces patterns of surface de-

fects which become visible under a source of ultra-violet light. The location, extent, and the general character of any surface imperfections are readily indicated by the fluorescent pattern. The method is known as Magnaglo analysis.

Another development, called Zyglo method, employs similar techniques as those used with Magnaglo inspection with the exception that the fluorescent medium may be applied to either magnetic or non-magnetic materials. Aluminum, magnesium, bronze, copper, and other non-ferrous materials may be examined for surface flaws.

In either case, the general scheme embodies the complete pre-cleaning of the surface to be examined, its immersion into the fluorescent liquid (a suitable fluorescent material dissolved in oil), and inspection under an ultra-violet light in a darkened booth. Since the examination is confined only to the surface of the material, the resultant indications should be evaluated accordingly.

CHAPTER XIV

THE ATOMIC STRUCTURE

PART I

The Atomic Theory

1. **Matter.**—(a) *The Molecule.*—We may define matter as a physical entity possessing properties characteristic to the corpuscular behavior of the particles constituting it. These particles may be classified, after Mosley's work, into about 92 different natural forms, or *elements*. Each element consists of small material particles that can not be seen by the naked eye yet can exist by themselves and retain all the characteristics of the original matter. An isolated unit quantity of such matter possessing all the properties of the original element is called a *molecule*. A molecule may be either an element or a compound. That is, all molecules of an element, regardless of its isotopic* nature, if any, are chemically the same; and, similarly, all molecules of a compound exhibit the same physical and chemical characteristics.

(b) *The Atom.*—We shall now return our attention to a state of affair which distinguishes a molecule from its precursor confined in the atom, and shall assign to the latter the property of chemical affinity. Consequently, an atom may be defined as the smallest structural unit of matter or an element that may, or may not, stand by itself and is capable of entering into a chemical reaction. Atoms combine by their relative weights determined by the extra-nuclear structure of each atom entering into the reaction.

One or more atoms of an element may stand for a molecule of the same element; and, when a molecule consists of a single atom it is called a *monatomic element*. If the molecule of an element consists of two atoms, it is known as a *diatomic element*; and, if more than two atoms enter into the making of an element, the latter is said to be *polyatomic*. Such atoms may be a gas, liquid, or a solid.

It should be noted that the physical states of atoms are only

*Isotopic refers to atoms with similar chemical properties but of different atomic weights.

relative for ordinary temperatures, and that the transition of an element from one state into another, by lowering or raising its temperature, is not uncommon. That is, a gas may be liquified by lowering its temperature; by heating a solid it may become liquified, or it may pass into a gaseous state by further increase in temperature; and, a liquid may be either solidified or be transformed into a gaseous form respectively by lowering or raising its temperature. In the case of certain solids, such as sulphur, the molecules may assume polyatomic structures under various temperature ranges.

2. The Structure of the Atom; Quantum Number of the Electron.—In considering the structural aspects of matter, or its integral unit, the atom, the question at once arises as to whether the atom should be looked upon as a unit matter at rest, or as one in action. The former state, we shall refer to as *static*, and the latter as *dynamic*.

The dynamic model is fashioned after the physicist's concept of material particles in activity as noted in the emission of radiations, their spectral importance in regard to the structure of the atom, or in the emanations from the disintegration of the radioactive substances, and the like. Much credit is attributed to Rutherford and Bohr in their active part in constructing this type of atom model, which, to the physicist, has become an indispensable "specimen" to work with. On the other hand, the static atom is the concern of the chemist, who weighs the atom and endeavors in an attempt to produce new combinations, and various complex compounds, formed by the interatomic affinity influenced by electrostatic forces inherent of the atom.

In discussing the structure of the atom, it will be more convenient to follow Lewis-Langmuir concept of an atom model of a state having no motion, and assumed to be isolated from all external influences. An atom of such character has definite physical and chemical properties in a given element. It consists of a nucleus of positive charge, surrounded by imaginary orbits bearing negative charges called electrons. The nucleus of an atom contains as many positive charges, or protons, as there are electrons in the atom. Thus, an atom at rest is electrically neutral, due to the interaction of electrostatic fields of electronic, and protonic origins. In an atom, some of the electrons are in the

nuclear region and are called the nuclear electrons, while the rest of the electrons occupy, in definite numbers, some specific orbits, and are known as extranuclear or orbital electrons. Approximately half of the total number of electrons occupy the nuclear region, and the other half are located in the orbits.

The number of chemical elements found in nature is fixed at 92, as mentioned before, and the atomic numbers of the elements are assigned according to the increasing atomic weights of the elements, starting from the lightest, the hydrogen, to the heaviest atom, the uranium. Incidentally, the atomic number of an element corresponds to the number of free positive charges* (protons) in the nucleus. Since the mass of the proton is approximately 1845 times that of the electron, the entire atomic mass is a function of the number of protons in the atom.

It has been evident from the experimental observations that, as proceeded along the successive elements from hydrogen to uranium, periodically occurring monatomic elements are encountered. These elements, in general, do not enter into any chemical combination with other elements, and, therefore, are known as inert gases, because the arrangement of the extranuclear electrons in these atoms is such as to render them a very stable structure. Hence, when the atoms of an element combine with those of others to form molecules or various compounds, the electron systems of these atoms arrange themselves in such a characteristic manner as to imitate the extranuclear electron configuration of the inert gases.

The spatial distribution of the extranuclear electrons in the inert gases may be expressed by a numerical order, originally grown from the observations of Rydberg. The number of the extranuclear electrons, Z , the atomic number, of the inert gases may be computed from the orbital distributions of the electrons characterized by the total quantum number n , as accepted at present.

The above is suggestive to the desirability of a reference to our previous assumption that electrons occupy extranuclear boundaries or orbital levels, designated by total quantum numbers, starting from the innermost level, the quantum number 1, next level, the quantum number 2, and so forth. For instance, the Krypton atom contains four levels, the first level of quantum number 1 contain-

*This corresponds to the number of orbital electrons.

ing 2×1^2 electrons; the second, the quantum number 2, 2×2^2 electrons; the third, the level of quantum number 3, 2×3^2 electrons; and the fourth, of quantum number 4, 2×2^2 electrons; and so on for other gases of the same series. As will be evident, the integers 2 and 8 suggest a symmetry of progression. Hence, in a chemical combination of active elements, the electrons assume such definite positions in the reacting atoms as to give an "*inert gas like*" structure to the outermost orbits of the atoms in this combination.

Elements	Atomic Numbers (Z)					
	n=1	n=2	n=3	n=4	n=5	n=6
He.....	$Z=2(1^2)=2$					
Ne.....	$Z=2(1^2 + 2^2)=10$					
Ar.....	$Z=2(1^2 + 2^2 + 3^2)=18$					
Kr.....	$Z=2(1^2 + 2^2 + 3^2 + 4^2)=36$					
Xe.....	$Z=2(1^2 + 2^2 + 3^2 + 4^2 + 5^2)=54$					
Nt.....	$Z=2(1^2 + 2^2 + 3^2 + 4^2 + 5^2 + 6^2)=86$					

The combining power of an atom is determined by the number of electrons occupying its outermost shell. For example, there are seven protons in the lithium nucleus, and seven electrons in the atom itself. Four of the electrons are located in the nucleus, two in the first atomic orbit, and one in the second. The chlorine atom has 35 protons and 35 electrons. It has 18 nuclear electrons, and 17 orbital electrons arranged in the order of 2 electrons in the first level (orbit), 8 in the second, and 7 in the third. Therefore, it will be readily seen that when a lithium atom, having 1 electron in its outermost orbit, and the chlorine atom, which needs 1 electron to complete its outermost level, come together in a chemical encounter, they unite to form a molecule of lithium chloride, by intersharing the lithium electron. The property of an atom of intersharing electron, or electrons, is known as the *valency* of that atom.

The valence of an atom is dependent on the number of electrons in its outermost orbit; and, in general, when an atom requires less than half of the maximum number of electrons to complete the outermost orbit, the atom will have a valence corresponding to the number of the "missing" electrons, and its valence will be minus. If an atom is "missing" more than half of its electrons in a given outermost orbit, the atom will have a plus valence cor-

responding to the number of electrons present in its outermost orbit.

As will be evident from the above discussion, each particular level bears only a definite number of electrons when completely filled up, the number of electrons in the outermost orbit determining the chemical properties of the atom in question.

3. The Atomic Structure, and Properties of Some Elements.

—When the chemical elements, with a few exceptions, are arranged in their increasing atomic weights, and each element is consecutively numbered from one, the element having the lowest atomic weight, to ninety-two, the element with the highest atomic weight, it will be found that the atomic number of any element will correspond to the number of extranuclear electrons in that element; and its atomic weight will correspond to the number of protons in its atomic nucleus. The atomic number may be accurately determined by mass spectrographic methods and from the X-ray spectrum of the element. The following atoms of various elements will illustrate, to our satisfaction, the simpler explanation of the atomic structure:

Element*	H	He	Li	Be	B	C	N	O	F	Ne	Na	Cl	Cu
At. No.	1	2	3	4	5	6	7	8	9	10	11	17	29
At Wt.	1	4	7	9	11	12	14	16	19	20	23	35	63
Protons	1	4	7	9	11	12	14	16	19	20	23	35	63
Neutrons	0	2	4	5	6	6	7	8	10	10	12	18	34
Nuclear Elec.	0	2	4	5	6	6	7	8	10	10	12	18	34
1st Level	1	2	2	2	2	2	2	2	2	2	2	2	2
2nd Level .....	.	..	1	2	3	4	5	6	7	8	8	8	8
3rd Level .....	.	..	..	..	..	..	..	..	..	..	1	7	18
4th Level .....	.	..	..	..	..	..	..	..	..	..	..	..	1

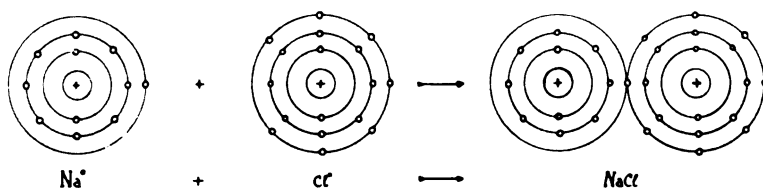
In the above illustration, the element lithium, ($Z = 3$), has 7 protons associated with its atomic weight of 7, and 7 electrons. Four of the electrons are in the nucleus, and 3 in the orbits, the latter number corresponding to the atomic number of the element. It will be further noted that 2 of the extranuclear electrons occupy a stable position around the nucleus of charge $+Ze$.

* Reference should be made to appendix for meanings of these chemical symbols of the elements.

The third electron, positioned in the second level relatively remote from the nucleus, so influences the nuclear plus charge as to initiate a distortion in the electrostatic field of the atom by concentrating the "lines of force" radially of the atom, and thereby producing an electric moment.

The two stable orbital electrons in the first level almost completely confine the attraction force of the plus nuclear charge from the valency electron in the second level, so that the latter electron becomes an agent comparatively free to move under favorable agitational influences. Lithium, then, is a monovalent, easily ionizable solid of good electrical conductivity. Likewise, the sodium atom ($Z = 11$), having its two inner shells completed and one electron to spare, should also be monovalent, and should exhibit similar chemical properties with those of lithium, as is the case.

The chlorine atom has 17 extranuclear electrons, of which, 2 are in the first level, 8 in the second, and 7 in the third level. Consequently, the vacant place in the outer level, which can only hold 8 electrons, may be filled by an electron as from a sodium atom during a chemical re-union with an atom of chlorine, as illustrated below.



It is to be observed that each of the two united atoms in the sodium chloride molecule has assumed an "inert gas like" structure—the sodium atom a neon-like, and the chlorine atom an argon-like structure—so that the combination is a very stable one. Thus, sodium chloride should be a crystalline non-conductor of high melting point. The salt, however, becomes electrolytically active when melted, or when dissolved in water.

4. The Atomic Charge and Electric Currents.—We have already seen that an atom is electrically neutral when it has an

equal number of electrons and protons. But, an atom may acquire a charge when the number of its orbital electrons is increased or decreased in respect to its normal structure. The atom becomes negatively charged when it gains one or more electrons in excess of its normal number of electrons; and, it acquires a positive charge by losing one or more electrons. Thus, the process in which an atom acquires an electrical charge is known as *ionization*.

In the example of the reaction of the sodium atom with chlorine, consider the resulting sodium chloride molecule is dissolved in many times its volume of water. The molecule dissociates into a sodium atom less one electron, and a chlorine atom with an excess of one electron than its normal number of electrons. In the process, the metallic radical, sodium, becomes positively charged due to one proton in excess of its electrons, and the non-metallic chlorine atom, gaining one electron from the metallic radical, becomes negatively charged. The sodium radical is now known as a positive sodium ion, and the chlorine radical as a negative chlorine ion. An ion, therefore, is the original atom having either a negative or a positive charge (or charges), depending on the number of electrons gained, or lost respectively.

In our picture of the conduction of electricity through an electrolytic solution by means of ions transferring these charges to the respective electrodes, the conduction in the external circuit takes place only by the migration of electrons.

It should be kept in mind, however, that an atom, by gaining or losing electrons, does not become altered into another atom, as no change is incurred in the number of protons. The variation in the normal number of electrons only alters an atom from one of neutral to a charged state.

The charge carried by each univalent ion (a singly ionized atom) may be determined by depositing a gram-atom of silver from a solution of silver nitrate. The number of unit electrical charges necessary to deposit one gram-atom of a univalent element, such as silver, is found experimentally to be 96,494 coulombs. But, by Avogadro's law, there are 6.06×10^{23} atoms in a gram-atom. Therefore, each univalent ion will carry a charge of 96,494 divided by 6.06×10^{23} atoms, which gives 1.59×10^{-19} coulomb, or 1.59×10^{-20} electromagnetic unit of charge, which, in terms of electrostatic units, is equal to $3 \times 10^{10} \times 1.59 \times 10^{-20}$,

which is equal to 4.79×10^{-10} e.s.u. This is approximately the magnitude of charge on the electron as determined by extremely accurate laboratory methods. Consequently, a univalent ion carries a charge of magnitude equal to that on an electron, regardless whether it is a negative or a positive ion, the difference of the two being one of polarity.

5. The Electron as a Unit Quantity of Electricity.—The presence of an equal number of charges of opposite polarities in an atom *at rest* causes in the atom a state of electrical neutrality, so that no electrical force exterior to the atom is observed. But, atoms may so dissociate into electrons and positive charges, as by magnetic means, or by an electrolytic action, that a continuous supply of electrons may be produced. These electrons, when made to travel through a suitable metallic conductor, constitute a current of electricity.

In metallic substances, the electrical conductivity is due to the presence of an atmosphere of electrons in motion. The effect of the application of an external force resides in the detachment of (some of) the planetary electrons from the atom and in the impressure of a definite average velocity of drift on these electrons in the direction of the impressed force gradient. This drifting of the electrons constitute the electric current, and since electrons bear only negative charges, the flow of electricity through metals must be a constituent of charges mostly of negative nature.*

In an undisturbed state, the metal has its free electrons in normal motion due to their potent heat. The energy of the heat motion of these electrons, however, may be increased by raising the temperature of the metal, and at sufficiently high temperatures, this energy will increase to the extent of carrying the electrons out through the surface of the hot conductor. Under these conditions, the heated body is capable of emitting negative, but not positive, electricity, since only the electrons take part in this transfer. Such an escape of negative electricity (electrons) from bodies at high temperatures is analogous to the evaporation of liquid molecules under heat, and is known as "*thermionic emission*," or "*Edison Effect*," in honor of the discoverer of the phenomenon. Further discussions of this effect will be found in chapters dealing

* It is believed that there are also positive ions which move radially, while the negative ions, or the electrons, move axially of the metallic conductor.

with the Absorption of Energy, and Thermionic Effects.

The electron is the smallest unit of electricity obtainable, and has an estimated charge of 4.80×10^{-10} e.s.u. Approximately 10^{19} electrons are equivalent to 1 coulomb, as given by the expression

$$Q = It \quad (126)$$

where, Q is the charge in coulombs, I the current in amperes, and t is the time (in seconds) the current is prolonged. Thus, a current of 1 ampere is constituted by approximately 10^{19} electrons flowing per second. We have already had occasion to discuss the practical unit of ampere in our treatment of electrodynamics.

6. The General Properties of An Electron.—The electron is the component unit negative charge of every atom. Since there is an equal number of negative and positive charges in a neutral atom, the electrical charge on the negative component of the atom must be equal to that on the positive component—the components being of opposite electrical polarities. The mass of the electron is approximately 1/1840 times that of the proton, yet the electrical charge that it bears is equally great to neutralize the charge on the proton. This fact is further evidenced in the even interchange of the positive and negative radicals in two ionized compounds in a chemical reaction.

Some of the principal properties attributable to the electron are:

- (1) All electrons are alike regardless of the atom or the orbit from which they are derived.
- (2) An electron always bears a negative charge equal to 4.802×10^{-10} electrostatic unit.
- (3) Electrons in a normal atom are in motion in stable orbits around the nucleus similar to that of planets around the sun.
- (4) Electrons can exist and move independently of the atom.
- (5) An electron has a mass of 9×10^{-28} gram, or 1/1845th of that of a proton.
- (6) The speed of an electron varies from 1/20th to full speed of light; i.e., approximately from 1,500,000,000 to 30,000,000,000 centimeters per second.

- (7) Electrons can be made to propagate at great speeds under electrical potentials, or voltage. The greater the impressed voltage on the electrons the faster they travel.
- (8) Electrons can be focused by means of electric, or magnetic fields.
- (9) Electrons are a source of energy—chemical, thermal, radiant, physiological, and, indirectly, mechanical.

Thus far, in this chapter, we have considered the mass of an electron moving with velocities small compared with that of light. However, when the speed of the electron approaches that of light, the mass, and hence, the charge of the electron increases with its velocity in accordance with the expression given in equation (6) as

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

in which, m_0 is the rest mass of the electron, v its velocity, and c is the speed of light. On the principle of relativity, this change in the electron mass at extreme velocities is expected, but, we should not draw any inferences that any material particle, such as an electron, may acquire the speed of light while in an isolated state. In the above equation, if $v = c$, then the electron will have an infinite mass, and, hence, an infinite kinetic energy, which fact is inconsistent with present experimental observations. The importance of the theory, however, rests in its use in the explaining of the interconversion of mass and energy in the light of the laws of conservation.*

PART II

The Nucleus

By bombarding thin sheets of metal with alpha-particles, Rutherford experimentally demonstrated his hypothesis that the positive charge of an atom is concentrated in a sphere of radius less than 10^{-12} cm. That when this sphere was approached radially by an alpha-particle the latter experienced a large deflection, and the forces between the particles and the nucleus increased ac-

* The reference to the "laws of conservation" includes the conservation of mass, energy, and, in certain cases, momentum.

cording to Coulomb's inverse square law. This at once explains the fact that the charge on the nucleus is identical with that on the proton, and that the mass of the atom is associated with the nucleus.

Accordingly, we may conclude that the entire mass of an atom is concentrated in its nucleus of charge $+Ze$, where, Z is the number of free protons corresponding to the atomic number of the atom, and e is the protonic charge equal in magnitude but opposite in polarity to that on the electron. Further evidence regarding the structure of the nucleus is brought to light through radioactivity, mass spectrographic methods, and more recently, through artificial disintegration of the atom by alpha-particles, and high speed protons and neutrons, or heavy hydrogen nuclei, produced by laboratory methods. All these yield significant evidence regarding the constituency of the atomic nucleus.

The nucleus of the atom is surrounded by Z electrons, which are assumed, according to Rutherford-Bohr atom model hypothesis, to be in constant motion in stationary orbits around the nucleus much the same way as the planets around the Sun. But, as was mentioned before, Bohr further assumes that these electrons accelerating in the stationary orbits do not radiate, and that in order to keep the electrons from being drawn into the nucleus due to the force of mutual attraction of the nuclear and electronic charges, this force is counter-balanced by a centrifugal force which tends to keep the electrons in their respective stationary orbits. The relation may be represented as

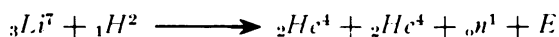
$$\frac{Ec}{r^2} = \frac{mv^2}{r} \quad (2)$$

in which, E and e are respectively the charges on the proton and the electron (which are equal numerically), and m is the mass of the electron and v is its velocity around the orbit of radius r .

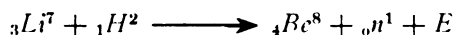
1. The Neutron.—We had stated previously that the nuclei of atoms consist of neutrons and protons. Now we shall modify this statement and say that all nuclei of atoms are made up of either protons, neutrons, or alpha-particles, or any combination of the first two or all of the three, depending on the size of the atom. A neutron may be thought of as a close union of a proton and an electron, so close together that they have neutralized each

other's electric field which is confined within the radius of the nucleus. Thus, the neutron has a mass very slightly greater than a proton, and is neutral, hence its name "*neutron*." Due to its zero charge, the neutron may penetrate matter further than either an electron or a proton. It traverses through atoms without being affected by their electric fields. With this reference, may we not now think of the neutron as a new element of zero atomic number, standing below hydrogen in the chemical series?

The sources of free neutrons are some of the artificial disintegration products of the lighter elements, such as lithium, beryllium, sodium, etc. When lithium of atomic weight 7 is bombarded with high speed deuterons, the nuclei of heavy hydrogen, the lithium nucleus splits into two alpha-particles, and a neutron, releasing a considerable amount of energy. The equation for this transmutation is given as follows:



An alternative reaction may take place, in which an atom of beryllium of atomic weight 8 together with 1 neutron are the resulting chemical products, as shown below.



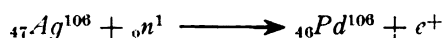
The superscript on the right of each atom corresponds to the atomic weight of the atom, while the subscripts on the left side are associated with the atomic number of the corresponding atom. Since a neutron has zero atomic number, it is denoted by a subscript "*o*". The energy E is generally given in million electron-volts. However, no attempt will be made at present to ascribe specific manifestations as may be exhibited by the neutron in its entering into the formation of the nuclei (until such time when further investigations of the neutrons have thrown more light on its nature).

2. The Positron.—The study of the photographs of cosmic ray tracks by means of a Wilson expansion chamber led to the discovery of the positron by C. D. Anderson¹ on August 2, 1932. He observed that the tracks made by the secondary electrons, pro-

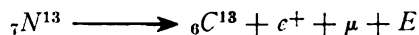
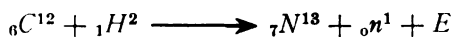
¹ Science, Vol. 76, pp. (1932).
Phys. Rev., Vol. 43, pp. (1933).

duced by cosmic rays, from a sheet of lead placed horizontally in the expansion chamber, had a definite direction of curvature and a range of several centimeters in air. However, in the course of his investigations, Anderson obtained a single track which had the same range as an electron track but of an opposite direction of curvature. The phenomenon could only be ascribed to positively charged particle of same magnitude of mass as that of an electron, since the ranges of the proton tracks were only a few millimeters due to the heavier masses of the protons. The new particle had the same magnitude of charge as that on the electron but of identical polarity as that on the proton. Thus, the inference was that the newly discovered entity was no more than a positive electron, to which Anderson gave the name "*positron*."

More recently, positrons are produced in the laboratory by the bombardment of the atomic nuclei by neutrons, and deuterons. Pool, Cork, and Thornton, of the University of Michigan, have demonstrated that the bombardment of silver atoms with high speed neutrons gives rise to radioactive silver of 25.5 minutes period together with the emission of positrons. The nuclear reactions may be represented as follows:



The emission of positrons from the deutronic bombardment of the lighter elements was also observed, as when carbon was bombarded with high speed deuterons, a positron and a neutrino were released in the reaction, which is given in the equations below.



in which, e^+ stands for a positron, and μ for neutrino, of which very little is known at the time of this writing.

3. The Positive Rays and the Mass Spectrograph.—Atomic masses of substances may be determined by passing a stream of positively charged ions through subsequent electric and magnetic fields surrounding the path of the ions in a discharge tube, and measuring the position of the deflection of the positive ions in-

cident upon a photographic plate in terms of a standard positive ion, such as oxygen of mass 16.0000.

These ions, frequently called positive rays, consist of atoms which have lost one or more of their planetary electrons under the influence of the impressed electrical potential. In a discharge tube, the positive ions are accelerated toward the cathode, dispersed by an externally applied electric field, and focused on a plane perpendicular to the magnetic field. The velocity of these particles depends on their charge and mass for a given constant potential. Ions having smaller mass will acquire higher velocities, and hence, they will deviate less than those ions that have greater masses. The principle constitutes a means of quantitative measurement of the masses of different atoms and their isotopes. Sir J. J. Thomson was the first to apply this method in measuring the value of e/m for the electron.

Subsequent investigations of the positive ion analysis have led to the development of slightly different methods of greater precision. The famous "*mass spectrograph*" of Aston consists of procuring increased dispersion of the positive ions under an electric field and bringing all the ions having the same ratio of E/M to a single focus on a photographic plate, thereby securing a mass spectrum consisting of dark bands in the developed plate. The essential parts of Aston's apparatus are shown diagrammatically in Fig. —.

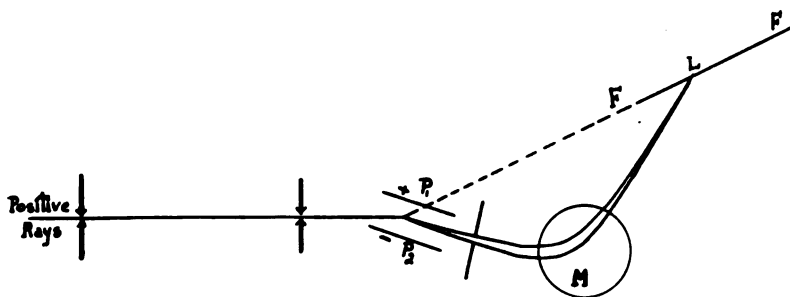


Fig. 177. Simplified Arrangement of Aston's Mass Spectrograph.

A stream of positive rays passing through the slits S_1 and S_2 is dispersed between the plates P_1 and P_2 impressed with an electric field of known intensity. The divergent beam, which contains ions of various velocities, emerges into a magnetic field M nor-

mal to the plane of the paper and is deflected upward, the ions having greater velocities being bent less than those moving with smaller velocities, so that all ions having a given ratio of E/M converge to the same region, as at L on the photographic plate $F-F$. Consequently, if there are more than one type of ions present in the discharge tube, the photographic plate will record black lines, each corresponding to the particular type of ions. Thus, a series of lines resembling an optical spectrum is obtained.

The significance of the apparatus lies essentially in its affording quantitative measurements of the masses of different isotopes which are chemically indistinguishable, and also in the determination of atomic masses in general.

A mass spectrograph devised by Bainbridge has the advantage of being more accurate, as it affords a direct measurement of the masses of the ions (having a given charge E) that are proportional to the radii of the curvatures they describe due to the magnetic field. The equation, below, illustrates the radius R as being a linear function of the ionic mass M , when the velocity of the ion is equal to F/H , where F and H are the strengths of the electric and magnetic fields respectively. The force exerted on the ion moving with a velocity v in a magnetic field H is equal to HEv , which is at right angles to the path of the ion. Therefore, in a magnetic field, the ion will describe a circle—at every point in that circle the force being at right angles to the direction of movement. We may thus express the forces in an equation form as

$$HEv = \frac{Mv^2}{R} \quad (143)$$

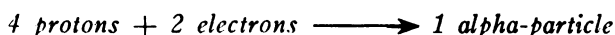
$$\text{or,} \quad R = \frac{Mv}{EH} \quad (144)$$

in which, R is the radius defined by the ion in the magnetic field H , while M and E are respectively the mass and the charge of the positive ion, and v is its velocity due to the electric field. By observing the position of R on the spectrographic film, the mass of any ion present in the system may be accurately determined; and, by computing the relative intensities of the "spectral" lines thus produced, the relative abundance of the isotopes of the elements are determined.

4. The Formation of Nuclei; the Packing Effect.—In our discussion of the mass spectrograph, the masses of different elements are determined on the unit of scale taking oxygen as having an atomic mass of 16.0000. We shall call this unit of scale the “*atomic mass unit*.” The data furnished by chemical methods on the mass of oxygen are based on the average mass of the mixture of oxygen isotopes of atomic masses 16, 17, and 18—the average chemical mass of oxygen being taken as 16.002, which is given in chemical mass units. Therefore, the conversion factor of chemical mass unit to one of atomic mass unit is 0.000125.

In a previous section, it was stated that the nuclei of atoms contain a mixture of protons, neutrons, and alpha-particles, the presence of which depending on the size of the atom. On this assumption, the nucleus of Li^7 contains 1 alpha-particle*, 3 protons, and 2 electrons. From Aston's work, the mass of the hydrogen atom is given as 1.00778 atomic mass units, and that of the electron as .00055 atomic mass unit. Hence, the mass of a proton is $1.00778 - .00055 = 1.00723$ atomic mass units.

Now, in the building up of a helium nucleus (the alpha-particle) from 4 protons and 2 electrons, there incurs a loss of .0288 atomic mass unit, as given by the following expression:

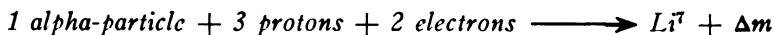


$$4 \times 1.0072 + 2 \times .00055 - 4.0011 = \Delta m_a$$

$$\Delta m_a = 4.0299 - 4.0011$$

$$\Delta m_a = .0288 \text{ a.m.u.}$$

where, the numerical quantity 4.0011 is the observed mass of the alpha-particle, Δm_a is the loss of mass in the reaction. For Li^7 , the mass loss in the nuclear formation may be given as



$$4.0011 + 3 \times 1.0072 + 2 \times .00055 +$$

$$3 \times .00055 \longrightarrow 7.012 + \Delta m$$

in which, 7.012 is the observed mass of Li^7 atom, and hence the

* Helium atom when doubly ionized becomes an alpha-particle.

addition of 3 electrons to the left hand side of the equation.

Computing the products of the terms, and re-arranging the equation, we have

$$4.0011 + 3.0216 + .0011 \longrightarrow 7.01035 + \Delta m$$

and,

$$\Delta m = .01345 \text{ a.m.u.}$$

which quantity is the loss of mass during the formation of the Li^7 nucleus from electrons, protons, and alpha-particle. The total loss of mass in the formation of Li^7 atom in the reaction of 7 protons and 7 electrons will, therefore, be

$$\Delta M = 7(1.0072) + 7(.00055) - 7.012$$

$$\Delta M = .04225 \text{ a.m.u.}$$

which value may also be found by adding the separately computed losses of mass in the Li^7 formation, as follows:

$$\Delta M = \Delta m_n + \Delta m$$

$$\Delta M = .0288 + .01345$$

$$\Delta M = .04225 \text{ a.m.u.}$$

This loss of mass is known as the “*mass defect*” of the atom, or, more generally, it is referred to as the “*packing effect*.” The packing effect for the atom, then, may be expressed in the form of the following equation:

$$\Delta M = P_n H_m - M_o \quad (145)$$

in which, M_o is the observed mass of the atom, P_n is the number of protons in its nucleus, and H_m is the mass of the hydrogen atom given as 1.00778 a.m.u.

The *packing fraction* of an atom is expressed by the mass defect per proton multiplied by 10,000; and, the equation form is

$$\Delta M_p = \frac{M_o - P_n}{P_n} \times 10,000 \quad (146)$$

where, ΔM_p is the packing fraction per proton per ten-thousand parts.

The packing fraction for the Li^7 atom is then

$$\Delta M_p = \frac{7.012 - 7}{7} \times 10,000 = +17$$

the plus sign before "17" indicating that the observed mass of the atom is greater than the number of protons contained in the nucleus.

Now, applying the relativity theory to the phenomenon of mass defect and computing the energy liberation ΔE due to the mass defect ΔM , we may express the mass-energy equivalence by the following general equation:

$$\Delta E = \Delta M c^2 \quad (147)$$

in which, c is the velocity of light, and the energy ΔE is numerically equal to 9×10^{20} ergs when ΔM is one gram. In practice, the energy ΔE is expressed in electron-volts. Then, we have

$$\Delta E = \Delta M c^2 = V e \quad (148)$$

where, V is given in electrostatic volts, and e is the charge on the electron. Converting V into practical volts, the expression becomes

$$1.649 \times 10^{-24} \Delta M c^2 = \frac{V \times 4.80 \times 10^{-10}}{300} \quad (149)$$

in which equation, ΔM is expressed in atomic mass units when multiplied by 1.649×10^{-24} , the mass of one atom of hydrogen.

Solving for V , the energy released in loss per atomic mass unit will be

$$\begin{aligned} V &= \frac{1.649 \times 10^{-24} \times 300 \times (3 \times 10^{10})^2 \Delta M}{4.80 \times 10^{-10}} \\ &= 9.33 \times 10^8 \Delta M \text{ volts.} \end{aligned}$$

$$\text{and, } \Delta E = 9.33 \times 10^8 \Delta M \text{ electron-volts.} \quad (150)$$

We shall thus note that in the formation of one lithium nucleus from electrons and protons the energy liberated for a loss of .04225 a.m.u. is

$$\begin{aligned} \Delta E &= 9.33 \times 10^8 \times .04225 \\ &= 39.42 \times 10^6 \text{ electron-volts.} \end{aligned}$$

which is the binding energy of the lithium nucleus. The binding energy of an atom is that amount of energy which is set free during the formation of the atomic nucleus, and is equivalent to the mass defect of the atom. The greater is this energy released during the nuclear formation the greater becomes the stability of the atom in question. For example, a helium atom is more stable than a carbon atom, since in the case of the former a greater loss of mass is experienced during the formation of its nucleus. Hence, we may conclude that the mass defect, packing fraction per atom, and the binding energy are closely related to each other in their equivalence of magnitude in a given atom.

Presently we shall consider some of the more recent work conducted in the field of nuclear transformation which will help us to correlate the mass and energy changes in the recombination or disintegration of the atomic components which have formed the basis of our discussion.

5. Transformation of Atoms.—We have already seen that the transformation of the atomic nucleus may be effected by the change in the number of neutrons in the nucleus. It was further observed that the nucleus of the atom could be made to increase in mass by the addition of a neutron during a positive ion bombardment reaction, and that it is possible that this reaction may so shift that an ultimate disintegration of the nucleus into nuclei of atoms of smaller atomic weights may result.

(a) *Radioactive Disintegration.*—In the case of the radioactive elements, the spontaneous nuclear decay results in the ejection of high speed alpha-particles. In consequence to the departure of these positively charged particles, the nucleus now with excess of two negative charges tends to re-establish its equilibrium and settles down to a new structure by further ejecting the remaining two negative particles, called *beta-rays*.* The re-establishment of the nuclear equilibrium by the transition of the nuclear electrons from a higher state to one of lower energy state is accompanied by a radiation of extremely short wavelength known as *gamma-ray*. The energy of a quantum of gamma-ray radiation represents the energy difference of any two energy levels of the Rutherford nuclear energy states between which the electron has made a transition. The average number of gamma-ray quanta emitted per

* The nuclear electrons when ejected from the atom are known as beta-rays.

second is in the order of 6×10^{10} , and the energy released from this radiation is about 9.4 calories per hour.

Ellis and Skinner have assigned to the nucleus seven energy levels, transitions in which give rise to gamma-radiations. The hypothesis is also supported by Rutherford who further suggests that, like extranuclear phenomena, there are electrons and helium-like structures (possibly a cluster of neutrons) in orbital rotation around a central body of sphere. By some yet unknown phenomena the positive part of one of these structures is detached and projected from the atom. The departure of the positive particles, or the alpha-rays, is followed by an emission of two beta-rays and the corresponding two quanta of gamma-radiation, an undetermined interval of time elapsing between each two of these emissions. The rays have their origin generally in uranium and thorium series of radioactive disintegration, the ultimate product of which forming the isotopes of lead of atomic weights respectively 206 and 208.

(b) *Artificial Disintegration*.—In the nuclear formation of the lighter elements it was pointed out that energies of the order of several million volts were liberated by loss of mass of the interacting nuclear components. Conversely, to completely disintegrate an element, energy, equivalent to the mass defect or the binding energy of the atom, must be absorbed by the atom in question. Owing to its large magnitude, the only source of such an energy, until recently, was the alpha-particle from Radium C. However, present day knowledge, together with modern apparatus, have made it possible to devise adequate methods of producing fast moving protons or other charged particles. These particles, accelerated directly by the application of a high voltage in one or more steps, are projected against a target of the pure element under observation with velocities in the neighborhood of that of light. The disintegration product of the target element thus bombarded depends upon the magnitude of the energy acquired by the atom from the bombarding particles.

We have already seen that in the formation of an alpha-particle* (helium nucleus) there incurred a mass loss of .0288 a.m.u., which is equivalent to nearly 27×10^6 electron-volts. Now, if it is desired to cause the complete disintegration of this particle into

* See Section 4, The Formation of Nuclei; Packing Effect.

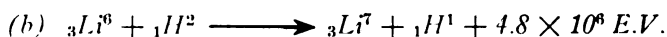
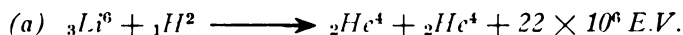
its constituent parts, it would require an energy in excess of 27×10^6 electron-volts, which is to be transferred to the target by the impinging particles.

Partial transmutation of the elements has been quite possible by bombarding the target consisting of the element under investigation with high velocity protons, deuterons (heavy hydrogen nuclei), and neutrons. To decide the nature of any reaction thus produced on the target, photographs of the various particle tracks formed in an expansion chamber are taken, and interpretations are made by the application of conservation laws in relation to the theory of relativity, by which the energy of the emitted particles may be expressed as

$$E = m_0c^2 = 9.33 \times 10^8 m \text{ electron-volts} \quad (151)$$

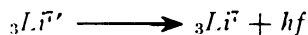
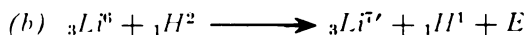
where, m_0 is the rest mass of the particle given in atomic mass units, m is the mass of the moving particle, and c is the velocity of light.

By bombarding ${}_3\text{Li}^6$ with deuterons of 500,000 volts, Walton and Cockroft have observed a pair of alpha-particles of range 12.6 centimeters, and protons of range 30 centimeters in an alternative reaction, as shown below.



In the second reaction, obviously the residual product is an atom of ${}_3\text{Li}^7$ due to the capture of the neutron from the ${}_1\text{H}^2$ nucleus.

The disintegration of lithium nucleus by deuterons of 100 - 250 kilovolt energy is reported by William, Shepherd, and Haxby. The reaction products are given in the accompanying equations:



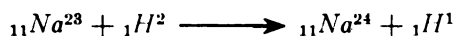
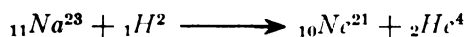
in which, ${}_3\text{Li}^{7'}$ is an atom of excited nucleus, and hf represents a quantum of radiation. The return of the excited lithium nucleus to a normal state is accompanied by the emission of a gamma-radiation (hf) of 400,000 electron-volt energy. Furthermore, it

was observed that with increased number of bombarding deuterons, the energy yield in the final product is increased.

E. O. Lawrence, of the University of California at Berkeley, has produced radioactive sodium by one hour exposure of a target of rocksalt crystal to the bombardment of high speed deuterons of 1.7 million volts energy. The activated sodium is said to decay with a half-life of 15.5 hours, emitting electrons, and gamma-rays with energies up to 1.2×10^6 electron-volts. The number of radioactive sodium atoms per second ranges as high as 4×10^8 . Radiophosphorus, $_{15}P^{32}$, is another element of great importance from the radiologist's standpoint because of its comparatively longer half-life, which is 14.3 days. The emission of gamma-rays is preceded by the disintegration of an equal number of beta-rays.

The fact that the nuclei of $_{12}Mg^{24}$, $_{6}C^{12}$, and $_{8}O^{16}$ all are of the same type in that they are made up of alpha-particles, presumably they are expected to exhibit similar excitation states.

The nuclear reaction of the sodium atom bombarded with the nuclei of heavy hydrogen (deuterons) may be expressed in the following equations:

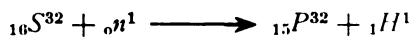
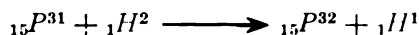
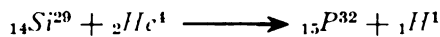


and,

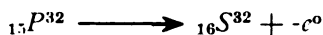


where, $-e^0$ stands for a beta particle and γ for a gamma-ray quantum.

Radiophosphorus may be produced by either one of the following reactions:

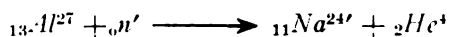


and, upon disintegration of $_{15}P^{32}$, beta-rays are emitted accompanied by gamma-rays. The reaction may be shown by the relation



in which, the final product is sulphur of atomic weight 32.

Fermi has produced radioactive sodium by bombarding ${}_{13}\text{Al}^{27}$ with neutrons. The reaction is given as follows:



in which, ${}_{11}\text{Na}^{24'}$ is an activated atom of sodium, which, by returning to its normal nuclear state gives off a quantum of gamma-radiation.

The significance of the production of radioactive sodium lies in the fact that the substance is comparatively much less expensive than radium; therefore, its therapeutic use in medicine makes it exceedingly important as it has a sufficiently long half-life period. Since the substance behaves, during its active life, as a source of gamma-rays, the radiation will affect a photographic film exposed to its influence. Hence, had x-rays not yet been discovered at present, it would not be improbable that the use of radiosodium in the field of radiography would be welcomed. Nevertheless, the development of the radioactive sodium occupies a prominent place in a field of its character in behalf of medical therapeutics.

CHAPTER XV

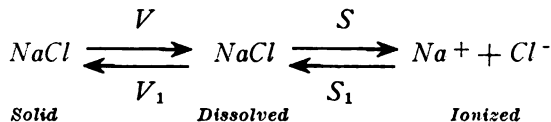
ABSORPTION OF ENERGY

In the normal state of an atom all its extranuclear electrons are in revolution in their lowest respective quantum orbits, a condition in which an atom possesses great stability. However, such a stationary state of an atom may be disturbed when one or more of the planetary electrons move up to a higher quantum state by an absorption of energy supplied as by a collision with an ion, or by thermal agitation. Such an atom is said to be in an *excited state*, and the process by which an atom is raised to an excited state is known as the *excitation* of that atom.

An excited atom, which has at least one of its electrons revolving in a higher quantum state, is unstable, and therefore, within about 10^{-8} second the atom assumes a stationary state by the return of the electron to its normal orbit, radiating a quantum of light energy. It may so occur that the energy of the electron is sufficiently great as to remove it completely from the atom, which condition leaves the atom with an excess of positive charge. This process is called *ionization*, and the atom is known as a positive ion, which, when free, will move about as in an electric field, or in an electrolytic solution. Each univalent ion carries a charge e equal to that on the electron but opposite in sign, and a divalent ion carries a charge $2e$, from which condition it is readily explainable that the ionization of an atom is characterized by the absence of its valency electrons. That is, an univalent atom is singly charged, while a divalent atom may become doubly charged, and in the case of trivalent or polyvalent atoms, the ionic charge depends upon the number of the valency electrons removed from the atom. Consequently, the energy required to excite or ionize an atom depends upon the orbital position and the quantum state of the electron which is displaced.

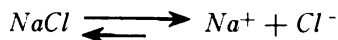
1. Electrolytic Ionization.—(a) *Solution of Molecules in Water.*—An electrolyte, such as a sodium chloride molecule, upon dissolving in water, dissociates into two oppositely charged radicals, or ions, and the solution cools due to energy absorption. The salt dissolves in a given amount of water in such quantities

as to satisfy a condition of molecular equilibrium between the dissociated and undissociated solute in the solution. When such an equilibrium is established, we have a condition as represented below.



in which, V and V_1 respectively represent the velocities of solution and saturation of $NaCl$ molecules; and, S is the speed of dissociation or ionization of the dissolved $NaCl$ molecules. Since the process is reversible to some extent, the speed with which the ions recombine to form the non-ionized $NaCl$ molecules is characterized by S_1 .

At equilibrium, i.e., when the ionizing molecules are equal in number to the recombining ions, the speed S is equal to S_1 , and V is equal to V_1 . But, generally the undissociated part is discriminated, and only the equation for dissociation is shown as



the linear magnitudes of the arrows conveniently indicating the extent of ionization, or recombination.

In the case of weak electrolytes, such as acetic acid, however, there is a constant relation between the dissociated and non-dissociated particles. This relation may be expressed in the following equation form:

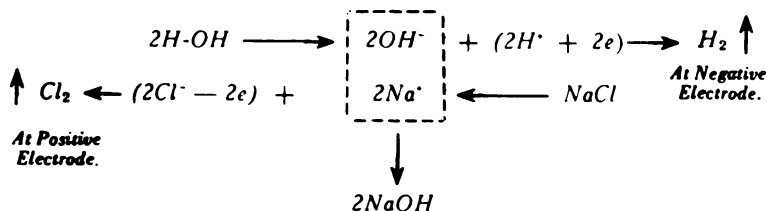
$$K = \frac{C_{H^+} \times C_{C_2H_3O_2^-}}{C_{HC_2H_3O_2}}$$

where, the larger C stands for "*concentration*," and K is the *ionization product* constant. It is apparent then that the dilution, within limits, of a weak electrolyte does not affect the number of the ions so produced, and therefore, the solution does not change in its electrical conductivity unless the dilution is exceeded beyond the value of K . Hence, the greater the value of K (greater solubility of the solute), the greater becomes the electrical conductivity, as there is a greater number of ions present per unit volume of the solution. In general, strong electrolytes,

such as copper sulphate, hydrochloric acid, sulphuric acid, etc., are highly ionized in an aqueous solution, and therefore, are better suited for electrolytic purposes, as in voltaic cells.

(b) *Electrolysis—Electrodeposition of Atoms.*—The above equilibrium equation for weak electrolytes does not apply in its simple form to strong electrolytes, owing to the large magnitude of the ionic concentration and to the electric forces between unlike ions tending to affect each other in that to exhibit an affinity towards recombination under favorable physical conditions. However, strong electrolytes generally are completely dissociated in a dilute aqueous solution, producing an equal number of positive and negative ions in proportion to their valences. These ions, which may be considered as electrical charges, are responsible for the conduction of electricity through an electrical field, or in an electrolytic solution.

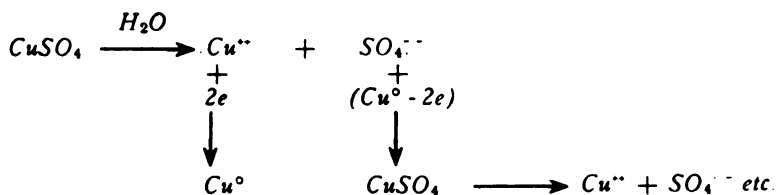
Considering again the solution of sodium chloride, for our discussion, when two electrodes are inserted into the solution and the circuit is completed by a battery of dry cells, the positive charges or the sodium ions are attracted towards the negative electrode, while the negative chlorine ions migrate towards the positive electrode. The ions, on reaching their respective electrodes, give up their ionic state by either acquiring electrons or transferring their excess electrons to the electrode with which they come in contact. Therefore, the chlorine ion abandons or discharges its excess electron to the positive pole and itself escapes from the solution as the nascent gas, while at the negative pole hydrogen is liberated instead of sodium, since the latter stands above hydrogen in the electrochemical series it displaces the hydrogen from the solution according to the reaction represented below.



where, e stands for an electron from either electrode. Thus, the process by which an electrolyte is electrically decomposed into its component radicals is called *electrolysis*.

The conductivity of an electrolytic solution depends on the concentration of the ions and on the mass, and hence the velocity, of the ions moving through the solution. Thus, the greater the number of ions and the faster they move to their respective electrodes, the greater will be the magnitude of the current passing through the solution per second. It is readily seen then that the greater the solubility of an electrolyte the higher is its electrical conductance. This fact is utilized in depositing metals electrolytically from their salt solutions on other metallic surfaces. It will not be out of place, however, to mention here that even liquid rubber may be made to deposit electrolytically on any conducting surface.

At present, practically most pure metals of commerce are obtained electrolytically. Copper, for example, may be deposited on a graphite cathode or a negative plate from a solution of copper sulphate. The anode or the positive plate is usually a lump of copper, and when the circuit is completed, the positively charged Cu ions migrate to the cathode, and acquiring negative charges from the electrode deposit on it as copper atoms. The sulphate radical from the solution is attracted to the copper anode, reacting with it to form $CuSO_4$ which re-establishes the copper sulphate equilibrium in the solution, as shown below.



The virtual effect of the phenomenon is the transfer of the copper atoms from the copper anode to the negative electrode. The process is widely used in producing commercially purified copper, and various other metals from their impure mineral states. The separation of different metals is made possible by the variance of their electrolytic response to the potentials impressed on the electrodes in the salt solution of the respective metals.

When different electrolytes are traversed by equal quantities of electricity, equivalent quantities of the metals are deposited on their respective cathodes. That is, it was already pointed out that an electrical energy of 96,494 coulombs in passing through an electrolytic solution liberates 1 gram-atom of a monovalent substance. Solutions containing divalent, and trivalent elements, respectively one-half, and one-third of their atomic masses will deposit electrolytically by this amount of electricity. Thus, 96,494 coulombs in passing through a silver nitrate solution will liberate 107.88 grams of silver; the same quantity of electricity will deposit 32.7 grams of zinc from a zinc sulphate solution; and, 9 grams of aluminum will deposit from its solution. This quantity of electricity which liberates 1 gram-equivalent of the element from its solution is called a *faraday*, and the principle is known as *Faraday's Law*.

In practice, the unit of current, the ampere, is generally employed. An ampere is one coulomb flowing for one second. The electrical intensity, or the volt, is the unit electrical potential difference between the electrodes in the conducting medium. Hence, if a current of 10 amperes is running through the electrolyte, it will take 2 hours, 40 minutes, and 48 seconds to pass a faraday of electricity through the solution at this rate.

2. Gaseous Ionization.—We have already discussed some phases of ionization in which an atom having lost, or gained, one (or more) electron becomes an electrically charged ion. In order that an atom may ionize, it must first absorb sufficient energy to expand the orbit of the rotation of the revolving electron in the outermost orbit; and, in an extreme case, the revolution of the electron may assume an orbit of radius of such magnitude that the electron may actually be released from the influence of the nuclear electrostatic field. At such an event, the electron becomes isolated from the atom and moves, in an electric field, in the direction of the potential gradient. In a gaseous discharge medium, the haphazardly moving electron, freed from the atom in the process of ionization, may acquire sufficient velocity by the intense electric field to produce new ions, upon collision, by transferring its kinetic energy to the colliding atoms. The electrons, expelled from the newly ionized atoms, proceeding toward the anode, repeat the process until they have exhausted the greater

portion of their kinetic energy to the atoms in the encounter, and ultimately becoming neutralized by the positive ions, or at the positive electrode.

Ordinarily, air is a poor conductor of electricity, but when two electrodes separated apart by a distance of a few centimeters in air are impressed with a high voltage, the air becomes highly conductive as the gaseous molecules become ionized. In this ionization, ions of both signs are present, and they move between and around the charged conductors, producing a purple corona discharge. The luminous effect is well noticed around the overhead aerials of an x-ray apparatus during the operation of the machine in a darkened room.

Since the air molecules readily ionize at the operating voltages of an x-ray machine, it suggests the desirability of installing the x-ray antenna well above reaching distance, thus avoiding the possibility of a spark discharge that may flash over to a person or technician standing beneath the aerial. In case the impressed potential on the electrodes is beyond that for a corona discharge, and the gaseous atmosphere in the space intermediate to the aerials is almost entirely ionized, there occurs a disruptive discharge between the oppositely charged conductors.

With a given applied potential, the occurrence of such a discharge is dependent upon the distance that the charged conductors are placed apart, and on the pressure and the humidity of the atmosphere. Therefore, advantage is taken of the phenomenon in the measurement of high potential differences such as exist in an x-ray circuit. The determination of the potential is made by producing a disruptive discharge between two spark spheres (usually several cms. in diameter) and measuring the distance of the gap under standardized atmospheric conditions as specified by charts prepared for this purpose.

Ionization may occur in a gaseous medium by various other agents, such as by alpha-particles from radioactive substances, x-rays, cosmic rays, and other electromagnetic waves. The general principle of such means of ionization resides in the transfer of energy in the form of kinetic energy, or quanta, to the neighboring atoms, and in the subsequent expulsion of electrons as a result of extreme excitation of the atoms, such an ionization being a direct function of the intensities of the inciting rays.

(a) *Production of Ions by Ultra-Violet Rays.*—When a gas is traversed by ultra-violet light the gaseous molecule may dissociate with the ejection of an electron and itself becoming positively charged. The effect, likewise known as ionization, is essentially a phenomenon of the atom being excited to a state whereby the electron vibration in its outermost orbit is raised to its *critical* or *threshold frequency*. If the incident quantum has a frequency f_0 equal to the threshold frequency of the electron, and transfers its energy hf_0 to the atom, the ionization of the latter results. The relation of the radiation and ionization energies is then given as

$$hf_0 = V_0 e \quad (152)$$

where, h is Planck's constant, f_0 the frequency of the radiation, V_0 is the ionization potential of the atom, and e the charge on the electron.

The above expression may be written in terms of the incident radiation wavelength λ , and therefore, the equation becomes

$$hf_0 = V_0 e = \frac{hc}{\lambda}$$

from which we obtain $\lambda = \frac{hc}{V_0 e}$

in which, when the ionization potential V_0 is known the wavelength of the radiation may be readily computed by substituting the numerical values of the other letters.

Gaseous ionization by means of electromagnetic waves, or quanta, is regarded as being effected by the radiation potential of the atom rather than its ionization potential, since the former potential may cumulatively rise to values far beyond the ionization potential of the atom. That is, different excited atoms may jointly transfer their energies of excitations to an electron of a stationary atom. If the energy absorbed is sufficient so as to cause the escape of the electron, the atom becomes ionized. The process is frequently known as *sensitized ionization*, in which, the energy of an excited atom, by colliding with another atom, appears in the latter atom by raising it to an ionized state, and later it radiates with a characteristic frequency.

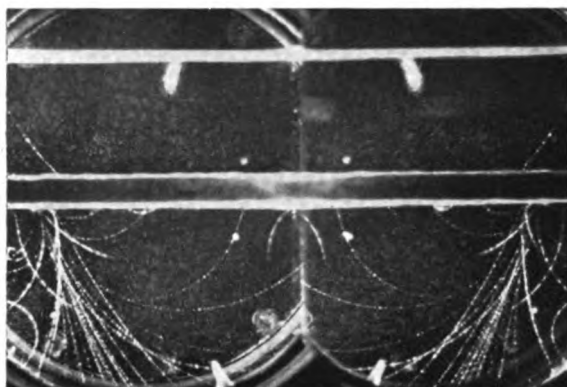
(b) *Production of Ions by X-Rays.*—Like ultra-violet light, x-rays, in their passage through air, dissociate the molecules into positive and negative ions. The effect may be detected when a beam of x-rays is incident upon a charged electroscope. The air surrounding the gold leaves of the electroscope becomes conducting, having been ionized by the x-ray beam. Some of the gaseous ions, possessing charges unlike those on the electroscope, are attracted to the charged leaves, and discharge the electroscope. Such a principle is fundamentally used as a quantitative means for the determination of x-ray therapy dosages. A device, known as the ionization chamber, in conjunction with an electrometer, measures the intensity, and, hence, the radiation dose absorbed by the body (or the film) exposed to the rays.

(c) *Production of Ions by Cosmic Rays.*—Rays having penetrating power of more than a hundred times that of an ordinary gamma-ray radiation shower the earth from all directions. They penetrate 18 feet of lead and can still be detected. Due to their origin, as believed to be somewhere outside of the earth, the rays are known as "*cosmic rays*."

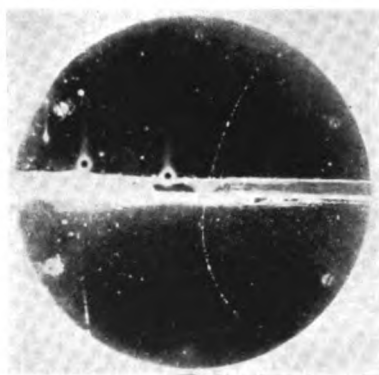
The exact character of the rays has not as yet been conclusively determined, but it is the present acceptance that the rays are of electromagnetic origin, and thus are identified with photons of extremely high frequencies. These photons travel with the speed of light, and produce visible tracks of their propagation when they traverse a Wilson expansion chamber. The nature of the rays, therefore, is deduced from the study of their secondary effects on especially gaseous mediums. In an expansion chamber, when the pressure of the column of air sealed above the surface of the water, or other fluid, contained in the trough of the chamber is suddenly released, beams of ionized vapor are projected into view by the occurrence of cosmic radiation at random through the apparatus. Careful investigations of these beams of ionized vapor have revealed that the energy of a cosmic quantum is of the order of 50 to 70 million electron-volts.

Cosmic rays ionize not only gases but also the atoms in solids. The phenomenon is better illustrated in the photograph below, in which an incident quantum of cosmic radiation ejects an electron from the lead sheet partitioning the expansion chamber. The path of the electron is described by the curvature of a vapor track

which consists of ionized water molecules clinging momentarily around the directional gradient of the projected electric field. The ionizing power of cosmic rays decrease abruptly at an under-water depth below 200 meters.



(a) Cosmic Ray Shower Causing the Release of Positive and Negative Particles in Pairs.



(b) The Track which Led to the Discovery of Positron on Aug. 2, 1931.

Fig. 178. Illustrating the Production of Positive and Negative Electrons by Incident Cosmic Rays on 6-mm Lead Plate.

(d) *Gaseous Ionization Produced by Alpha-Particles.*—In the process of decay, certain radioactive substances, such as uranium, thorium, or radium, emit positively charged alpha-particles, which, when allowed to pass through a gaseous atmosphere ionize the gas

molecules. The effect is particularly prominent when the alpha-particles are made to project across the Wilson cloud-chamber. The traveling alpha-particle by collision with the vapor particles along its path ionizes them. The newly-ionized particles, in turn, attract other vapor molecules so that each ion becomes surrounded with a cluster of vapor molecules held together by a "nucleus" of charged ion, whatever the origin of the ion may be. The effect is a momentary appearance of a track of cloud along the entire path of the alpha-particle. The length or the range of this track of vapor is a quantitative measure of the kinetic energy of the emitted alpha-ray. Therefore, by comparison of the range of the emerging ion (or any other positive ion) with an ion of known range as a standard, the kinetic energies of various ionized particles can be accurately determined.

Geiger, in his measurement of the ranges of alpha-particles, found that a single alpha-particle from Radium C could foster ionization to nearly 4.4×10^5 particles, half of which consisted of electrons, and the other half of positive ions. But, an alpha-particle is ejected from Radium C with an energy of approximately 7×10^6 electron-volts. If this entire energy is used up for the ionization of air molecules, then it will take an average energy of $7 \times 10^6 \div 2.2 \times 10^5 = 32$ electron-volts to produce a pair of ions of unlike charges under standard atmospheric conditions.

By bombarding Li^7 with protons of sufficient energy, Oliphant produced a pair of alpha-particles of ranges 8.3 cms. each, and of a total energy of about 17×10^6 electron-volts. For helium nucleus of mass 3, (${}_2He^3$), the range is longer than that of mass 4. Thus, lighter particles, such as protons, and neutrons, have longer ranges for a given initial energy.

It must be well kept in mind that these observations of the charged particles are made in an expansion chamber, the characteristic manifestations being due to the ionization of the vaporous particles along the entire path of the traveling charged particles. Therefore, it is only the secondary effects of these emissions that afford the determination of the nature and the energies of the ions of different masses.

(c) *Ionization by Electron Impact and by Applied Potential.*—The ionization of gases may also be effected by impressing a sufficiently high potential on the electrodes in a discharge tube

containing a gas at a relatively low pressure. The electric field due to the charged electrode at first ionizes some of the surrounding gaseous atoms, releasing electrons from them. Thus, two kinds of ions are simultaneously produced in the medium intervening the electrodes—positive ions, and negative ions or electrons, having haphazard directions of movement.

The electrons are accelerated at high speed by the intense electric field toward the positive electrode and acquire kinetic energy, while the positive ions travel to the cathode at comparatively lower speeds because of their heavier masses, and, upon colliding with the electrode they release more electrons from it, with the result that the discharge medium is filled up with unlike ions traveling in the opposite directions—the positive ions moving toward the cathode, and the electrons to the anode. However, a great many of the positive ions are neutralized by collision with electrons, and still others return to their normal state with the emission of characteristic radiations which illuminate the entire medium between the electrodes.

An electron, by colliding with an atom of a gas or vapor, may transfer some of its kinetic energy to one of the electrons in the extranuclear region of the atom, and continues in its movement with a change in direction and velocity. If during the collision, the atom experiences an increase in energy sufficient to expel an electron from one of the stationary orbits to infinity, the atom is said to have ionized; and, the collision, in which the atomic energy is increased due to the transfer of kinetic energy from the colliding electrons, is known as an *inelastic impact*. In the event that the energy received by the atom is not sufficient to raise it to an ionized state, then the atom becomes merely excited as a result of one of the orbital electrons making a transition to a higher energy level. On the other hand, a collision may give rise to an increased kinetic energy in the atom without affecting its internal energy; the atom then moves in a direction slightly different to that of the initial path of the electron of impact. In such an energy transfer, the electron proceeds without appreciable decrease in its initial velocity, and makes other collisions with the neighboring atoms until its entire energy is exhausted, and finally becoming attracted to the positive electrode.

The excited atom is in an unstable state, and, therefore, it re-

turns to its normal state with the emission of a photon; or, by colliding with the walls of the cathode, the atom releases an electron by conveying energy to the electrode during the impact. The electron, acquiring a speed proportional to the impressed potential, will undergo similar series of collisions with the atoms of the gas until finally it uses up all its energy. It is then attracted to the anode by the electrostatic field.

(f) *Thermionic Emission of Negative Ions.*—In a previous chapter mention was made that in an atom at rest the extranuclear electrons possess normal distribution of thermal velocities, which, when increased by rise of atomic temperature may excite the

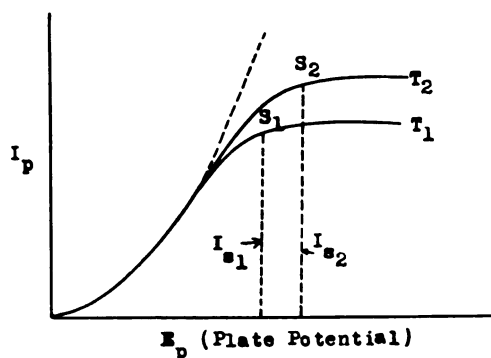


Fig. 179. The Characteristic Curve of Two-Element Vacuum Tube.

atom. Thus, the increase in velocity of the electron, and hence an increase in energy in the atom may so agitate the electrons that some of them may actually escape from the surface of the atom. Such an escape of electrons from metallic bodies heated to high temperatures is called "*thermionic emission of electrons.*" The higher the temperature of the metal the greater is its emissive power. In a vacuum tube, if the cathode filament is heated to incandescence and a sufficiently high potential is applied a stream of negative ions or electrons will proceed to the cold anode but not in the reverse direction, since no electrons can be released by the cold electrode. Most of the ions discharged from the hot filament are of electronic nature. It may be inferred, therefore, that in a vacuum tube there exists only a negative electricity as

the discharge medium consists largely of electrons, and only a negligibly few positive ions are released due to the evaporation of the electrode metal. Thus, in the succeeding paragraphs, thermal emission of only electrons will be dealt with.

With a given cathode temperature, the number of electrons arriving at the anode varies with the impressed potential within a limited extent beyond which the electron current becomes saturated so that any increase in potential does not appreciably increase the electron emission. The effect is expressed graphically in the Fig. (179).

In the figure, I_p represents the anode current, which reaches saturation at the point S_1 at a temperature T_1 . Increasing the cathode temperature to a new value, as to T_2 , the tube current I_p reaches saturation at S_2 with an increased applied potential. I_{s1} and I_{s2} are respectively the saturation currents due to the filament temperatures T_1 and T_2 . At high temperatures, the electron emission will vary considerably in that a slight variation in the heating current will produce a marked change in the electron emission.

In order that an electron can escape from the surface of the heated metal it must acquire sufficient kinetic energy from the thermal agitation of the atom to overcome the potential barrier offered by the corresponding positive charge in the metal. The electron thus emerging from the surface of the metal expends an amount of energy given as

$$E_p = e\phi \quad (153)$$

where, e is the charge on the electron (4.80×10^{-10} e.s.u.), and ϕ is the work function of the metal, or the difference of potential in volts offered by the positive charge against the escape of the electron from the metallic surface. The numerical value of ϕ varies for different metals, the alkali metal group having the lowest work functions. This last quantity may be expressed in either electron-volts or in ergs.

The cathodes of radio tubes are frequently coated with an alkali earth oxide, such as barium oxide, strontium oxide, etc., and sometimes with thorium oxide. The oxide lowers the surface work function of the metal so that the electron emission increases a hundred times. Thus, the cathode filament may be operated at much lower temperatures which curtails a saving in the heating

current, and prolongs the life of the filament. However, the oxide coated filaments will not be of any advantage in high potential tubes, such as in x-ray rectifying tubes, due to the disintegration of the coating by the excessive electrostatic forces and by the ionic bombardment both during the processing of the tube and during its normal operation, if such oxide be left on the filament after the exhaustion of the tube.

The phenomena of the emission of electrons from hot bodies find numerous practical uses in the field of radio, television, telephony, x-rays, and in other electric industries. The thermionic valve, functioning as an amplifier, or as an oscillator, has proved itself invaluable both in the field of radio and in medical diathermy; and, when used as a rectifier, it has especially contributed to the advent of the modern x-ray tubes, which, owing to the accurately controllability of the thermionic emission of the electrons, possess current stability incomparable with that of old-fashioned gas tubes. The electron-gun, on the other hand, as the most precise architect and sculptor, producing images, electron by electron, on the fluorescent coating of the television-receiving tubes, adds its importance to the progress of the modern electric age.

APPENDIX

APPENDIX I

ELEMENTS AND THEIR CHARACTERISTICS

Element	Symbol	At. No.	At. Wt.	Melting Point °C.	Specific Gravity
Actinium.....	Ac	89	227.00	.....	.....
Alabamine.....	Ab	85	221.00	.....	.....
Aluminum.....	Al	13	26.97	660	2.70
Antimony.....	Sb	51	121.76	630.5	6.68
Argon.....	A	18	39.94	-189.2	1.27 g/l
Arsenic.....	As	33	74.93	814.0	5.73
Barium.....	Ba	56	137.36	850.0	3.50
Beryllium.....	Be	4	9.02	1350.0	1.85
Bismuth.....	Bi	83	209.0	271.0	9.78
Boron.....	B	5	10.82	2300.0	2.54
Bromine.....	Br	35	79.91	-7.2	3.12 liq.
Cadmium.....	Cd	48	112.41	320.9	8.65
Calcium.....	Ca	20	40.08	810.0	1.54
Carbon.....	C	6	12.00	> 3500.0	2.25 graph.
Cerium.....	Ce	58	140.13	640.0	6.90
Cesium.....	Cs	55	132.81	26.4	1.87
Chlorine.....	Cl	17	35.45	-101.6	3.2 g/l
Chromium.....	Cr	24	52.01	1615.0	7.1
Cobalt.....	Co	27	58.94	1480.0	8.9
Columbium.....	Cb	41	93.30	1950.0	8.4
Copper.....	Cu	29	63.57	1083.0	8.95
Dysprosium.....	Dy	66	162.46	.....	.....
Erbium.....	Er	68	167.64	.....	4.77
Europium.....	Eu	63	152.00	.....	.....
Fluorine.....	F	9	19.0	-223.0	1.69 g/l
Gadolinium.....	Gd	64	157.30	.....	.....
Gallium.....	Ga	31	69.72	29.75	5.91
Germanium.....	Ge	32	72.60	958.5	5.36
Gold.....	Au	79	197.20	1063.0	19.32
Hafnium.....	Hf	72	178.60	1700.?	13.30
Helium.....	He	2	4.00	< -272.2	0.177 g/l
Holmium.....	Ho	67	163.50	.....	.....
Hydrogen.....	H	1	1.0078	-259.1	0.0899 g/l
Illinium.....	Il	61	146.00	.....	.....
Indium.....	In	49	114.80	155.0	7.28
Iodine.....	I	53	126.93	113.5	4.93 sol.
Iridium.....	Ir	77	193.10	2350.0	22.42
Iron (cast).....	Fe	26	55.84	1275.0	7.85
Krypton.....	Kr	36	82.90	-169.0	3.7 g/l
Lanthanum.....	La	57	138.90	826.0	6.15
Lead.....	Pb	82	207.22	327.5	11.35
Lithium.....	Li	3	6.94	186.0	0.534
Lutecium.....	Lu	71	175.00	.....	.....
Magnesium.....	Mg	12	24.32	651.0	1.74
Manganese.....	Mn	25	54.93	1260.0	7.20
Masurium.....	Ma	43	.....	.....	.....
Mercury.....	Hg	80	200.61	-38.87	13.59
Molybdenum.....	Mo	42	96.00	2620.0	10.20
Neodymium.....	Nd	60	144.27	840.0	6.95
Neon.....	Ne	10	20.18	-248.67	0.9 g/l
Nickel.....	Ni	28	58.69	1452.0	8.90
Nitrogen.....	N	7	14.008	-209.86	1.25 g/l

APPENDIX I—*Continued*
ELEMENTS AND THEIR CHARACTERISTICS

Element	Symbol	At. No.	At. Wt.	Melting Point °C.	Specific Gravity
Osmium.....	Os	76	190.80	2700.00	22.48
Oxygen.....	O	8	16.00	-218.4	1.42 g/l
Palladium.....	Pd	46	106.70	1555.0	11.40
Phosphorus.....	P	15	31.02	44.1	1.8-2.2
Platinum.....	Pt	78	195.23	1755.0	21.45
Polonium.....	Po	84	210.00	.....	.....
Potassium.....	K	19	39.10	62.3	0.86
Proseodymium..	Pr	59	140.92	940.0	6.50
Protactinium....	Pa	91	.....	.....	.....
Radium.....	Ra	88	225.97	960.0	5.0
Radon.....	Rn	86	222.00	.....	9.73 g/l
Rhenium.....	Re	75	186.31	3000.?	20.53
Rhodium.....	Rh	45	102.91	1955.0	12.50
Rubidium.....	Rb	37	85.44	38.5	1.53
Ruthenium.....	Ru	44	101.70	.....	12.20
Samarium.....	Sm	62	150.43	> 1300.0	7.7
Scandium.....	Sc	21	45.10	1200.0	2.5
Selenium.....	Se	34	79.20	220.0	4.5
Silicon.....	Si	14	28.06	.....	2.42
Silver.....	Ag	47	107.88	960.5	10.50
Sodium.....	Na	11	22.997	97.5	0.97
Strontium.....	Sr	38	87.63	800.0	2.6
Sulphur.....	S	16	32.06	120.0	2.07
Tantalum.....	Ta	73	181.40	2850.0	16.6
Tellurium.....	Te	52	127.50	452.0	6.24
Terbium.....	Tb	65	159.20	.....	.....
Thallium.....	Tl	81	204.39	303.5	11.85
Thorium.....	Th	90	232.12	1845.0	11.20
Thulium.....	Tm	69	169.40	.....	.....
Tin.....	Sn	50	118.70	170.0	5.7-6.5
Titanium.....	Ti	22	47.90	1800.0	4.5
Tungsten.....	W	74	184.00	3370.0	19.3
Uranium.....	U	92	238.14	< 1850.0	18.68
Vanadium.....	V	23	50.95	1710.0	5.87
Virginium.....	Vi	87	224.00	.....	.....
Xenon.....	Xe	54	131.30	-140.0	5.85 g/l
Ytterbium.....	Yb	70	173.50	.....	.....
Yttrium.....	Y	39	88.92	1490.0	5.51
Zinc.....	Zn	30	65.38	419.4	7.14
Zirconium.....	Zr	40	91.22	1700.0	6.40

APPENDIX II

IMPORTANT PHYSICAL CONSTANTS

Electrical Units:—

Charge (quantity):—

Electronic Charge (e) ..	$= 4.802 \times 10^{-10}$ e.s.u.
	$= 1.592 \times 10^{-20}$ e.m.u.
	$= 1.592 \times 10^{-19}$ coulomb.
Coulomb (Q)	$= 10^{-1}$ e.m.u.
	$= 3 \times 10^9$ e.s.u.
	$= 6.28 \times 10^{18}$ electronic charges.
Microcoulomb (μQ) ...	$= 10^{-6}$ coulomb.
Faraday	$= 96,500$ coulombs.

Current:—

Ampere (I)	$= 10^{-1}$ e.m.u.
	$= 3 \times 10^9$ e.s.u.
	$= 1$ coulomb per second.
	$= 1.036 \times 10^{-5}$ faraday per second.
Milliampere (MA)	$= 10^{-3}$ ampere.
Micro-ampere (μA) ...	$= 10^{-6}$ ampere.

Potential:—

Volt (E or V)	$= 10^8$ e.m.u.
	$= 10^8$ gausses.
	$= 1/3 \times 10^{-2}$ e.s.u.
Kilovolt (KV)	$= 1000$ volts.
Million-Volt (MV)	$= 10^6$ volts.
Millivolt	$= 10^{-3}$ volt.
Microvolt	$= 10^{-6}$ volt.

Resistance:—

Ohm (R or r)	$=$ The resistance of a uniform column of mercury 106.3 cms long, at 0° C., having a mass of 14.452 grams.
	$= 10^9$ e.m.u.
	$= 1/9 \times 10^{-11}$ e.s.u.
Megohm	$= 10^6$ ohms.
Microhm	$= 10^{-6}$ ohm.
	$= 10^{-12}$ megohm.

Capacity:—

$$\begin{aligned}\text{Farad (C)} & \dots\dots\dots = 10^{-9} \text{ e.m.u.} \\ & \qquad \qquad \qquad = 9 \times 10^{11} \text{ e.s.u.} \\ & \qquad \qquad \qquad = 10^6 \text{ microfarads.} \\ \text{Microfarad } (\mu\text{C}) & \dots\dots\dots = 10^{-6} \text{ farad.} \\ \text{Micro-microfarad } (\mu\mu\text{C}) & = 10^{-12} \text{ farad.}\end{aligned}$$

Inductance:—

$$\begin{aligned}\text{Henry (L)} & \dots\dots\dots = 10^9 \text{ e.m.u.} \\ & \qquad \qquad \qquad = 1/9 \times 10^{-11} \text{ e.s.u.} \\ \text{Millihenry} & \dots\dots\dots = 10^{-3} \text{ henry.}\end{aligned}$$

Magnetic Units:—

$$\begin{aligned}1 \text{ line of force} & = 1 \text{ maxwell} = 1 \text{ e.m.u.} = 10^{-8} \text{ volt-second.} \\ 1 \text{ gauss} & = 1 \text{ maxwell/sq. cm.} = 1 \text{ line/sq. cm.} \\ 1 \text{ gilbert} & = 1 \text{ gauss-centimeter.} \\ \text{Magnetron (Bohr)} & = 9.22 \times 10^{-21} \text{ erg per gauss.}\end{aligned}$$

Other Constants:—

$$\begin{aligned}\text{Velocity of Light} & \dots\dots\dots = \frac{\text{Electrostatic Unit}}{\text{Electromagnetic Unit}} \\ & \qquad \qquad \qquad = \frac{\text{e.s.u.}}{\text{e.m.u.}} = 3 \times 10^{10} \text{ cms/second.}\end{aligned}$$

$$\text{Positron Charge (positive electron)} = 4.802 \times 10^{-10} \text{ e.s.u.}$$

$$\text{Positron Mass} = 9.107 \times 10^{-28} \text{ gram.}$$

$$\text{Electron Mass} = 9.107 \times 10^{-28} \text{ gram.}$$

$$\text{Mass of Proton} = 1.672 \times 10^{-24} \text{ gram.}$$

$$\text{e/m} = 5.2741 \times 10^{17} \text{ e.s.u. per gram.}$$

$$\text{Electron-volt} = 1.59 \times 10^{-12} \text{ erg.}$$

$$1 \text{ erg} = 0.629 \times 10^{-12} \text{ electron-volts.}$$

$$\text{Gas Constant (R)} = 1.9864 \text{ calories/degree/mole.}$$

$$= 8.3136 \times 10^7 \text{ ergs/degree/mole.}$$

$$\text{Avogadro's Number} = 6.06 \times 10^{23} \text{ per mole.}$$

$$\text{Planck's Constant} = 6.55 \times 10^{-27} \text{ erg-second.}$$

$$\text{Boltzmann's Constant} = 1.3708 \times 10^{-16} \text{ erg/degree.}$$

$$\text{Grating Space of Rock Salt (NaCl)} = 2.8 \text{ A.U. (approx.)}$$

$$\text{Grating Space of Calcite (CaCO}_3\text{)} = 3.0 \text{ A.U. (approx.)}$$

Grating Space of Mica $= 9.9 \text{ A.U. (approx.)}$

Grating Space of Quartz (SiO_2) $= 4.2 \text{ A.U. (approx.)}$

Gravitational Constant (G) $= 6.66 \times 10^{-8} \text{ C.G.S. Units.}$

Radius of Earth (Equatorial) $= 6.3784 \times 10^8 \text{ cms.}$

Mean Density of Earth $= 5.52 \text{ grams per Cc.}$

Mean Distance From Earth to Sun $= 1.495 \times 10^{13} \text{ cms.}$

Mean Distance From Earth to Moon $= 3.844 \times 10^{10} \text{ cms.}$

APPENDIX III
INTERNATIONAL WEIGHTS AND MEASUREMENTS
Units of Length

Angstrom Units	Microns	Millimeters	Centimeters	Inches	Meters
1	10^{-4}	10^{-7}	10^{-8}	2.5×10^{-8}	10^{-10}
10^4	1	10^{-3}	10^{-4}	2.5×10^{-4}	10^{-6}
10^7	10^3	1	1/10	1/25	10^{-3}
10^8	10^4	10	1	2/5	10^{-2}
2.54×10^8	2.54×10^4	25.4	2.54	1	1/39
10^{10}	10^6	10^3	10^2	39.4	1

1 light year = 5.9×10^{12} miles = 9.5×10^{12} kilometers.

1 kilometer = 10^3 meters = 10^5 cms. = 10^6 millimeters.

1 mile = 1760 yards = 5280 feet = \times 63,360 inches.

1 yard = 3 feet = 36 inches = .9144 meter

1 foot = 12 inches = .3048 meter

1 inch = 2.54 centimeters

1 meter = 1.093 yards = 3.279 feet = 39.37 inches.

UNITS OF AREA

1 square meter = 100 sq. decimeters = 10^4 sq. cms. = 10^6 sq.mms.

1 square mile = 640 acres = 3,097,600 sq. yds. = 27,878,400 sq. ft.

1 acre = 4840 sq. yds. = 43,560 sq. ft.

1 sq. yd. = 9 sq. ft.

1 sq. ft. = 144 sq. ins.

UNITS OF VOLUME

1 cubic meter = 10^3 cubic decimeters = 10^6 cu.cms. = 10^9 cu.mms.

1 cubic decimeter = 10^3 cu.cms. = 10^6 cu.mms.

1 Cc = 10^3 cu.mms.

The weight of 1 Cc of water at 4°C. is 1 gram.

UNITS OF CAPACITY AND EQUIVALENTS

1 liter = 1000 Cc = 1000 milliliters

1 Cc = 1 milliliter = 16.2 minims (drops)

APPENDIX IV(a)

ETCHING REAGENTS FOR ALUMINUM AND ITS ALLOYS

No. 1, General; Microscopic

Hydrofluoric Acid.....	0.5 Cc
Distilled Water to make.....	100.0 Cc

Swab with soft cotton for 10 to 15 seconds, and wash.

No. 2, General; Microscopic

Sodium Hydroxide.....	10.0 grams
Distilled Water to make.....	100.0 Cc

Immerse specimen in solution for 5 seconds at 70°C. Rinse in cold distilled water.

No. 3, For General Microscopic

Nitric Acid.....	25.0 Cc
Distilled Water to make.....	100.0 Cc

Immerse specimen in solution at 70°C. for 40 seconds. Quench in cold water, and wash with distilled water.

No. 4, Keller's Etchant

(For microstructure of duraluminum and for spot welds)

Hydrofluoric Acid.....	1.0 Cc
Hydrochloric Acid.....	1.5 Cc
Nitric Acid.....	2.5 Cc
Distilled Water to make.....	100.0 Cc

Immerse specimen in solution for 10 to 15 seconds, and wash in running water while gently swabbing the surface with cotton until contrast result.

No. 5, General ; Microscopic

Hydrofluoric Acid.....	4.5 Cc
Hydrochloric Acid.....	13.5 Cc
Nitric Acid.....	4.5 Cc
Distilled Water to make.....	30.0 Cc

Immerse specimen for 10 to 15 seconds, and wash under warm running water, swabbing the surface of specimen until black deposit disappears and contrast results.

Excellent for spot weld examinations.

APPENDIX IV(b)

ETCHING REAGENT FOR MAGNESIUM AND ITS ALLOYS

No. 1, Glycol Etchant

Diethylene Glycol	75.0 Cc
Distilled Water.....	24.0 Cc
Nitric Acid.....	1.0 Cc

Swab specimen with cotton soaked with the etchant for 10 to 15 seconds, or until grain boundaries clearly appear.

No. 2, For Wrought Alloys

Malic Acid.....	5.0 grams
Nitric Acid.....	2.0 Cc
Distilled Water to make.....	100.0 Cc

Immerse specimen in solution and agitate slightly for 10 to 20 seconds, and wash with distilled water.

No. 3, For Cast and Wrought Alloys

Oxalic Acid	2.0 grams
Distilled Water to make.....	100.0 Cc

Swab the surface of specimen, and wash with distilled water.

No. 4, For Dow-H Type Alloys

Tartaric Acid.....	2.0 grams
Distilled Water to make.....	100.0 Cc

Swab specimen for 2 to 10 seconds until contrast results.

MICROSCOPIC IDENTIFICATION OF CONSTITUENTS
IN
SAND CAST DOWMETAL ALLOYS

Element	Optimum Condition for Detection	Unetched		Etched with Glycol for 2-5 Seconds	
		Shape	Color	Shape	Color
Ag	Etched	Speckled	Gray	Speckled	Gray
Al (Mg ₂ Al ₃)	Etched	.....	.....	Globular	White
Al-Zn	Etched	.....	.....	Globular*	White
Zn (MgZn ₂)	Etched	.....	.....	Filigreed	White
Cd**	.....	.....	.....	.....	.....
Cu (Mg ₂ Cu)	Etched	.....	.....	Globular; Network.	White; Iridescent
Ni (Mg ₂ Ni)	Etched	.....	.....	Globular; Network.	White
Si (Mg ₂ Si)	Etched; Unetched	Angular; Script	Blue Gray	Angular; Script	Blue Gray
Mn	Unetched	Rounded	Dark Gray	Rounded	Dark Gray
Sn (Mg ₂ Sn)	Etched	Network	Blue	Massive Network	Brown to Purple

*The constituent is present as a gray lamellar structure when in the precipitated condition.

**Cadmium is completely soluble in Dowmetal and forms no microscopically visible constituent.

See "Dowmetal Laboratory Methods" for further information.

APPENDIX IV(c)

ETCHING REAGENTS FOR NICKEL AND ITS ALLOYS

No. 1, Flat Solution

(For Nickel, Monel, and Other Nickel-Copper Alloys)

Nitric Acid.....	50.0 Cc
Glacial Acetic Acid.....	50.0 Cc

*(Make up fresh daily.)**Immerse or swab specimen for 5 to 20 seconds.**Dilute with 25 to 50 per cent acetone for alloys of less than 25 per cent nickel.*

No. 2, Cyanide Persulphate Etchant

*(Grain boundaries of Nickel, Monel and Nickel-Copper Alloys)***Stock Solution A**

Sodium Cyanide	10.0 grams
Distilled Water to make.....	100.0 Cc

Stock Solution B

Ammonium Persulphate	10.0 grams
Distilled Water to make.....	100.0 Cc

For use:—Take equal volumes when ready to use.

Immerse or swab specimen for 5 to 9 seconds under hood.

No. 3, Electrolytic Etchant

(Grain boundaries of Nickel, and Nickel-Copper Alloys)

Sulphuric Acid	10.0 Cc
Distilled Water to make.....	100.0 Cc

Etch specimen as anode for 15 to 30 seconds, using platinum cathode and 1.5 to 6 volts.

No. 4, Electrolytic Contrast Etchant

*(Grain size studies of Nickel, Monel, and
Nickel-Copper Alloys)*

Nitric Acid.....	10.0 Cc
Acetic Acid.....	5.0 Cc
Distilled Water to make.....	100.0 Cc

*Etch with specimen as anode for 20 to 60 sec-
onds, using platinum cathode and 1.5 volts.*

No. 5, Monel Contrast Solution

(For grain contrast)

Chromic Acid.....	3.0 grams
Nitric Acid.....	10.0 Cc
Ammonium Chloride	5.0 grams
Distilled Water	90.0 Cc

*Immerse or swab specimen
for 10-60 seconds.*

No. 6, Macro-etch for Nickel Silver

Nitric Acid	30.0 Cc
Distilled Water to make.....	100.0 Cc

Etch by immersion.

No. 7, Microetch for Nickel Silver

(High Zinc content)

Hydrogen Peroxide.....	15.0 Cc
Ammonium Hydroxide	85.0 Cc

Etch by immersion

APPENDIX IV(d)

ETCHANTS FOR COPPER AND ITS ALLOYS

No. 1, Peroxide Etchant

Ammonium Hydroxide.....	25.0 Cc
Distilled Water.....	25.0 Cc
Hydrogen Peroxide (3%).....	20.0 Cc

Etch by immersion or swabbing.

No. 2, Persulphate Etchant

Ammonium Hydroxide.....	20.0 Cc
Distilled Water.....	20.0 Cc
Ammonium Persulphate (5%).....	20.0 Cc

Etch by immersion.

No. 3, Chromic Acid Etchant

(For Aluminum Bronze)

Chromic Oxide.....	6.0 grams
Nitric Acid.....	15.0 Cc
Distilled Water.....	9.0 Cc

Etch by immersion or swabbing gently.

No. 4, Dichromate Etchant

(For Beryllium-Copper, Etc.)

Sodium Chloride (Sat. sol.).....	3.0 Cc
Sulphuric Acid.....	6.0 Cc
Potassium Dichromate.....	1.5 grams
Distilled Water to make.....	80.0 Cc

Make solution fresh, Etch by immersion.

No. 5, Electrolytic Etchant

Sodium Hydroxide.....	0.2 grams
Ferrous Sulphate.....	1.5 grams
Sulphuric Acid.....	5.0 Cc
Distilled Water to make.....	100.0 Cc

*Etch at 8 to 10 volts and 100 milliamperes for
10 to 15 seconds.*

APPENDIX IV(e)
ETCHANTS FOR LEAD AND LEAD ALLOYS

No. 1, Acetic-Nitric Etchant
(For Macrographing)

Acetic Acid (glacial).....	13.0 Cc
Nitric Acid.....	17.5 Cc
Distilled Water to make.....	100.0 Cc

Use fresh Etch by immersion at 40°C for 5 to 25 minutes. Wash in running water by swabbing with cotton.

No. 2, Silver Nitrate Etchant

Silver Nitrate.....	5.0 grams
Distilled Water to make.....	90.0 Cc

Etch by swabbing.

No. 3, Electrolytic Etchant

Perchloric Acid.....	15.0 Cc
Distilled Water to make.....	25.0 Cc

Etch specimen as cathode at 8 volts and 1.5 amperes. Use platinum anode.

APPENDIX IV(f)

ETCHING REAGENTS FOR MICROSCOPIC EXAMINATION OF
IRON AND STEELNo. 1, Nital Etchant
(For Carbon Steel)

Nitric Acid.....	2.0 Cc
Ethyl or Methyl Alcohol.....	125.0 Cc

*Etch specimen for a few seconds by immersion
or by swabbing.*

No. 2, Picral Etchant
(For Carbon Steel)

Picric Acid.....	5.0 grams
Ethyl or Methyl Alcohol.....	125.0 Cc

*Etch specimen for a few seconds by immersion
or by swabbing.*

No. 3, Electrolytic Etchant
(For Carbon Steel)

Chromic Trioxide	8.0 grams
Distilled Water to make.....	90.0 Cc

*Use specimen as anode, and platinum as cathode.
Using 5 to 6 volts etch for 45 to 90 seconds.*

No. 4, Chromic Reagent
(For Stainless Steels; Spot Welds)

Chromic Trioxide (10% sol.).....	30.0 Cc
Hydrochloric Acid.....	25.0 Cc

*Etch specimen by immersion, wash in hot run-
ning water, and re-etch by swabbing. Wash in
hot water, and dry at once. Use solution fresh.*

No. 5, Ferricyanide Etchant
(For Stainless Steels)

Potassium Ferricyanide.....	18.0 grams
Potassium Hydroxide.....	18.0 grams
Distilled Water to make.....	40.0 Cc

Use fresh. Etch specimen in boiling solution until contrast results.

No. 6, Cupric-Magnesium Etchant
(For Segregation and Strain Lines)

Cupric Chloride.....	0.75 grams
Magnesium Chloride.....	3.10 grams
Hydrochloric Acid	1.00 Cc
Distilled Water	15.00 Cc
Ethyl Alcohol to make.....	80.0 Cc

Etch specimen by swabbing. Remove copper deposit by 20% solution of ammonium persulphate. Wash in hot running water.

No. 7, Oxalic Acid Etchant
(For Carbides in Stainless Steel)

Oxalic Acid	2.0 grams
Distilled Water	100.0 Cc

Etch electrolytically with 0.5 amperes and 5 volts for 60 to 90 seconds, or until desired etch results.

APPENDIX IV(g)

MACRO-ETCHING REAGENTS FOR IRON AND STEEL

No. 1, General Macro-etchant For Steel

Hydrochloric Acid.....	5.0 Cc
Distilled Water to make.....	50.0 Cc

Etch specimen at 80°C for 15 to 60 minutes until desired contrast or flow lines result.

No. 2, Persulphate Etching Reagent
(For Flow Lines and Grain Contrast)

Ammonium Persulphate.....	15.0 grams
Distilled Water.....	100.0 Cc

Etch specimen by swabbing. If excessive contrast occurs, remove deposit with dilute hydrochloric acid, and re-etch.

No. 3, Cupric-Ferric Etchant
(For Segregations and Strain)

Cupric Chloride.....	4.5 grams
Ferric Chloride	4.5 grams
Hydrochloric Acid	8.0 Cc
Ethyl Alcohol to make.....	80.0 Cc

Dissolve salts in least amount of water and add the alcohol and then acid.

Etch specimen heated to 400°F by immersing in the etchant for a few seconds until a contrast etch results.

APPENDIX V(a)
MECHANICAL PROPERTIES OF ALUMINUM SAND-
CASTING ALLOYS*

Minimum Values for Specifications			Typical Values		
Alloy	Tension		Tension		
	Ultimate Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches	Yield Strength (Set = 0.2%) Lb./Sq. In.	Ultimate Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches
43	17,000	3.0	9,000	19,000	6.0
47	24,000	5.0	11,000	26,000	8.0
108	19,000	1.5	14,000	21,000	2.0
112	19,000	....	14,000	23,000	1.5
122-T2	23,000	....	20,000	25,000	1.0
122-T61	30,000	....	30,000	36,000	1.0
142-T2	23,000	....	18,000	27,000	1.0
142-T61	32,000	....	32,000	37,000	0.5
142-T571	29,000	....	28,000	32,000	0.5
195-T4	29,000	6.0	16,000	31,000	8.5
195-T6	32,000	3.0	22,000	36,000	5.0
195-T62	36,000	....	31,000	40,000	2.0
212	19,000	....	14,000	22,000	2.0
214	22,000	6.0	12,000	25,000	9.0
220-T4	42,000	12.0	25,000	45,000	14.0
A334	22,000	....	16,000	25,000	2.0
355-T6	32,000	2.0	25,000	35,000	3.5
355-T51	25,000	....	23,000	28,000	1.5
A355-T51	25,000	....	24,000	28,000	1.5
A355-T59	23,000	....	21,000	25,000	2.0
356-T4	26,000	5.0	16,000	28,000	6.0
356-T6	30,000	3.0	22,000	32,000	4.0
356-T51	23,000	....	20,000	25,000	2.0
645	25,000	2.5	20,000	29,000	4.0

*Accompanying tables are reproduced by permission of Aluminum Company of America.

APPENDIX V(b)
MECHANICAL PROPERTIES OF ALUMINUM
PERMANENT-MOLD CASTING ALLOYS

Minimum Values for Specifications			Typical Values		
Alloy	Tension		Tension		
	Ultimate Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches	Yield Strength (Set = 0.2%) Lb./Sq. In.	Ultimate Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches
43	21,000	2.5	9,000	24,000	6.0
A108	24,000	....	16,000	28,000	2.0
B113	24,000	....	19,000	29,000	1.5
C113	25,000	....	24,000	28,000	0.5
C113-T2	24,000	....	14,000	27,000	1.5
122-T52	30,000	....	31,000	35,000	0.5
122-T65	40,000	....	36,000	48,000	0.0
122-T551	30,000	....	35,000	37,000	0.0
122-T553	27,000	....	32,000	34,000	0.0
A132-T4	34,000	....	30,000	38,000	1.5
A132-T551	31,000	....	28,000	36,000	0.5
138	26,000	....	24,000	28,000	0.5
142-T61	40,000	....	42,000	47,000	0.0
142-T571	34,000	....	34,000	40,000	0.0
B195-T4	33,000	4.5	22,000	40,000	10.0
B195-T6	35,000	2.0	33,000	45,000	5.0
A214	22,000	2.5	16,000	27,000	5.0
355-T51	26,000	....	24,000	30,000	2.0
355-T6	37,000	1.5	26,000	43,000	4.0
356-T4	28,000	5.0	18,000	32,000	9.0
356-T6	33,000	3.0	24,000	40,000	5.0

APPENDIX V(c)
TYPICAL MECHANICAL PROPERTIES OF ALUMINUM
DIE-CASTING ALLOYS

Alloy	Typical Mechanical Properties		
	Tensile Strength Lb./Sq. In.	Yield Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches
13	33,000	18,000	1.8
43	29,000	13,000	3.5
81	32,000	24,000	1.3
82	44,000	.....	0.2
83	30,000	14,000	3.5
85	35,000	19,000	2.7
93	33,000	20,000	1.0
218	38,000	23,000	5.0

APPENDIX V(d)
TYPICAL MECHANICAL PROPERTIES OF
WROUGHT ALUMINUM ALLOYS

Alloy and Temper	Yield Strength (Set = 0.2%) Lb./Sq. In.	Ultimate Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches		Hardness
			Sheet Specimen ($\frac{1}{8}$ Inch Thick)	Round Specimen ($\frac{1}{2}$ Inch Diameter)	Brinell, 500-kg. Load 10-mm. Ball
2S-O	5,000	13,000	35	45	23
2S- $\frac{1}{4}$ H	13,000	15,000	12	25	28
2S- $\frac{1}{2}$ H	14,000	17,000	9	20	32
2S- $\frac{3}{4}$ H	17,000	20,000	6	17	38
2S-H	21,000	24,000	5	15	44
3S-O	6,000	16,000	30	40	28
3S- $\frac{1}{4}$ H	15,000	18,000	10	20	35
3S- $\frac{1}{2}$ H	18,000	21,000	8	16	40
3S- $\frac{3}{4}$ H	21,000	25,000	5	14	47
3S-H	25,000	29,000	4	10	55
11S-T3	42,000	49,000	..	14	95
11S-T8	44,000	57,000	..	14	100
17S-O	10,000	26,000	20	22	45
17S-T	40,000	62,000	20	22	100
Alclad 17S-T	33,000	56,000	18	..	..
A 17S-T	24,000	43,000	..	27	70
24S-O	10,000	26,000	20	22	42
24S-T	45,000	68,000	19	22	105
24S-RT	55,000	70,000	13	..	116
Alclad 24S-T	41,000	62,000	18	..	..
Alclad 24S-RT	50,000	66,000	11	..	..
52S-O	14,000	29,000	25	30	45
52S- $\frac{1}{4}$ H	26,000	34,000	12	18	62
52S- $\frac{1}{2}$ H	29,000	37,000	10	14	67
52S- $\frac{3}{4}$ H	34,000	39,000	8	10	74
52S-H	36,000	41,000	7	8	85
53S-O	7,000	16,000	25	35	26
53S-W	20,000	33,000	22	30	65
53S-T	33,000	39,000	14	20	80
61X-O	8,000	18,000	22	..	30
61S-W	21,000	35,000	22	..	65
61S-T	39,000	45,000	12	..	95

APPENDIX V(c)
MECHANICAL PROPERTIES OF ALUMINUM ALLOY FORGINGS

Minimum Specification Values

Alloy	Tension			Hardness
	Yield Strength (Set = 0.2%) Lb./Sq. In.	Ultimate Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches	Brinell, 500-kg. Load 10 mm. Ball
11S-T	34,000	55,000	12.0	90
14S-T	50,000	65,000	10.0	130
17S-T	30,000	55,000	16.0	100
18S-T	40,000	55,000	10.0	100
25S-T	30,000	55,000	16.0	100
32S-T	40,000	52,000	5.0	115
A51S-T	34,000	44,000	14.0	90
53S-T	30,000	36,000	14.0	75
70S-T	40,000	50,000	16.0	85

APPENDIX V(f)
MECHANICAL PROPERTIES OF ROLLED MAGNESIUM SHEET

Alloy Designation	Condition or Treatment	Ultimate Strength Lb./Sq. In.	Yield Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches
		Typical	Typical	Typical
AM2S-O	Annealed	27,000	14,000	15.0
AM2S-H	Hard rolled	37,000	27,000	9.0
AM3S-O	Annealed	32,000	17,000	16.0
AM3S-H	Hard rolled	36,000	27,000	9.0
AMC52S-O	Annealed	38,000	25,000	18.0
AMC52S-H	Hard rolled	46,000	34,000	10.0
AMC57S-O	Annealed	42,000	26,000	10.0
AMC57S-H	Hard rolled	50,000	35,000	6.0

MECHANICAL PROPERTIES OF MAGNESIUM FORGINGS

Alloy Designation	Condition or Treatment	Ultimate Strength Lb./Sq. In.	Yield Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches
		Typical	Typical	Typical
AMC57S	Press forged	42,000	26,000	8.0
AMC58S	Press forged	45,000	30,000	6.0
AM65S	Hammer forged	38,000	22,000	12.0
AMC74S	Press forged	41,000	24,000	16.0
AMC74S-T5	Press forged and aged	42,000	28,000	14.0

APPENDIX V(g)
MECHANICAL PROPERTIES OF MAGNESIUM SAND,
PERMANENT MOLD, AND DIE CASTINGS

Alloy Design		Tension		
		Yield Strength Lb./Sq. In.	Tensile Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches
Amer. Mag. Corp.	The Dow Chemical Co.	Typical	Typical	Typical
AM246-C	Dowmetal-B	14,000	19,000	0.5
AM246-T6	Dowmetal-B	20,000	32,000	0.5
AM260-C	Dowmetal-C	14,000	23,000	1.5
AM260-T4	Dow C-T4	14,000	39,000	10.0
AM260-T6	Dow C-T6	20,000	38,000	3.0
AM265-C	Dowmetal-H	11,000	27,000	6.0
AM265-T4	Dow H-T4	12,000	37,000	9.0
AM265-T6	Dow H-T6	18,000	36,000	4.0
AM230-C	Dowmetal-K	22,000	32,000	1.5

APPENDIX V(h)
TYPICAL MECHANICAL PROPERTIES OF STEELS USED
IN AIRCRAFT MATERIALS

S.A.E. No.	Yield Strength Lb./Sq. In.	Tensile Strength Lb./Sq. In.	Elongation, Per Cent in 2 Inches	Reduction in area Per Cent
1020	25,000	45,000	22	..
1035	50,000	80,000	20	..
1050	75,000	100,000	16	..
1120	35,000	55,000	14	40
2330	100,000	125,000	15	50
2340	110,000	135,000	15	50
2515	145,000	170,000	14	45
3115	90,000	130,000	16	40
X3140	100,000	130,000	17	50
4130	100,000	125,100	18	50
X4130	75,000	95,000	12	45
6135	120,000	150,000	15	50
6150	200,000	220,000	10	40
Nitralloy	80-100,000	100-135,000	15-20	40-55

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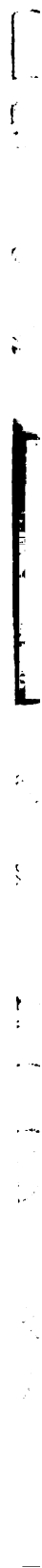
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